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FIBER OPTICS FOR NAVAL APPLICATIONS: AN ASSESSMENT OF PRESENT AND NEAR-TERM CAPABILITIES

NAVAL RESEARCH LABORATORY,
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Fiber Optics for Naval Applications: An Assessment of Present and Near-Term Capabilities

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Material Sciences Division

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This report provides an overview of the present status and envisioned future role of fiber optics for naval applications. Subjects addressed include state-of-the-art materials and fibers, their optical and mechanical properties, environmental testing, design of fibers and cables, and fiber systems. Present problem areas are outlined as well as their recommended or anticipated solutions. Some specific avionic, undersea, and shipboard applications of fiber-optic systems are discussed along with the advantages and expected payoffs with deployment. A listing of key Navy and industrial laboratories, manufacturers, and principal investigators in the fiber-optic area has also been provided.

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FIBER OPTICS FOR NAVAL APPLICATIONS: AN ASSESSMENT OF PRESENT AND NEAR-TERM CAPABILITIES

1.0 OBJECTIVE

The purpose of this report is to provide a brief overview of the present status and the envisioned future role of fiber optics for Naval applications. Subjects addressed include state-of-the-art materials and fibers, their optical and mechanical properties, environmental testing and degradation, fiber and cable design, typical systems employing fibers and the expected payoffs. Present problem areas are discussed as well as their recommended or anticipated solutions. In addition, we have attempted to identify many of the key laboratories, manufacturers and principal investigators presently engaged in the fiber optic area. The task of this report has been confined to a discussion of fiber cables and repeaters only, so that evaluation of sources, detectors, couplers, modulators, connectors and other optical systems components has been omitted. It has not been our attempt to prepare a comprehensive document covering all present day and future Navy programs in the fiber optic area, but rather to provide a concise summary which addresses the important concepts, advantages and problem areas of fiber optic technology. For those seeking more detailed information on specific subjects dealing with fiber optics, a bibliography has also been provided.

2.0 BACKGROUND

The operation of a fiber waveguide is governed by the simple laws of geometrical optics and electromagnetic theory. Light injected into a fiber at the proper angle will undergo internal reflection at the walls and will propagate along the length of the fiber until attenuated by absorption and scattering mechanisms. By cladding the central core material of the fiber with a lower-index material to achieve a protected, reflective interface, and through the use of homogeneous, ultrahigh-purity glasses, attenuations of less than 1 db/km have been achieved in optical fibers, far lower than have been obtained in conventional coaxial cables. Typical losses in operational fiber cables are now in the 5 to 10 db/km range. A basic fiber communication link consists of a modulated light source such as GaAs light-emitting diode (LED) or laser diode, the fiber waveguide, repeaters to periodically amplify the signal, and a photodetector such as silicon PIN or avalanche diode. Operation is normally confined to the near-infrared region ($.8\mu < \lambda < 1.06\mu$), which corresponds to the maximum transmission region of the fiber waveguide.

Present day fiber materials include high purity silicas, doped silicas, silicate glasses and various polymers. Fiber core-cladding geometries fall into three principal categories: 1) step-index multimode, in which fiber cores typically range from 50 to 100μ diameter, 2) graded index, in which the index of refraction decreases continuously with increasing distance from the fiber axis, and 3) single-mode step-index, in which core diameters are reduced

to a few microns so that only one mode will propagate. The difference in index of the core and cladding materials determines the angle of light acceptance of a fiber, i.e., its numerical aperture (NA). Typical NA's of optical fibers range from 0.1 to 0.6, which correspond to an angular acceptance range of 11.5 to 73.5 degrees. Cladding thickness and the NA of a fiber also affect the minimum radius to which a fiber can be bent before light is ejected and lost from the waveguide and are therefore important for both microbending and cross-talk problems.

The bandwidth of an optical fiber is limited primarily by mode and material dispersion. Both of these effects cause a light pulse injected in one end of a fiber to broaden as it propagates down the waveguide. In the mode dispersion case, axial modes travelling the shortest distance along the fiber will arrive before those repeatedly reflected off the walls of the waveguide. Material dispersion results since the velocity of light in an optical material is frequency dependent. Therefore light from broad-banded light sources such as LED's spreads out as it travels along the fiber. The material dispersion problem can be minimized by the use of narrow spectral sources such as laser diodes. The modal dispersion can be sharply reduced by the grading of the fiber index over its crosssection, thereby equalizing the effective optical path traversed by all rays regardless of mode. Thus most present day fibers for long distance, high-data-rate applications are of the graded index type. Finally, the mode dispersion of fibers can be eliminated entirely by going to a small ($d \approx$ few microns) single mode fiber. This type of fiber must be interfaced with a coherent laser source and requires further development before eventual deployment.

Most early fiber optic systems have employed so-called "bundle" technology in which many fibers are packaged together in a single link, all carrying the same signal. This redundancy was necessary largely because of the high probability of breakage in long length cables and the off-the-shelf nature of components which could couple to the fiber bundles. However, as reliability increases and the cost of ultralow loss glasses remains high, the trend is towards single multimode fiber cable configurations, each with its own discrete light source and detector, with perhaps 4 to 6 single fibers incorporated into an actual cable design.

The question which must be repeatedly asked for each Navy application is "Why use fiber optics?". Advantages include wide bandwidth, small size, light weight, low cross talk, electrical isolation, near neutral buoyancy, low attenuation, EMI and RFI immunity, EMP immunity, increased security, high thermal stability, and fabrication from non-strategic materials. For any given application, any one of these advantages may be sufficient to justify the use of a fiber link. On the negative side, there is the present high cost of low-loss fiber cables and the serious question of the mechanical reliability of fiber cables. In the past breakage,

especially in long lengths, has not been uncommon. The effects of stress corrosion on fiber strength remain uncertain at the present time. In addition, stress-induced optical losses in deployed cables can substantially increase the optical losses measured in the laboratory under ideal conditions. It is essential to take a hard look at optical fibers to see whether they are capable of withstanding actual field conditions and severe environments.

In preparing this summary, we have attempted to determine the state of the art of fiber optic materials, fibers and cables including their design, their optical and mechanical properties, the degree of environmental testing performed or ongoing. We have also outlined many present and envisioned Navy systems applications for fiber optics, and the dividends expected from fiber deployment. Future directions are also discussed. In the Appendices we have provided a list of the Tri-Service Fiber Optic Committee members and their respective responsibilities as well as a breakdown of industrial and Naval Laboratories currently engaged in various aspects of fiber optic technology, and the responsible individuals within these organizations.

3.0 PRESENT STATUS

3.1 Fiber Cable Materials

The preparation of high quality fiber optic cables requires a wide range of materials with specific mechanical, optical, electrical and chemical properties. These can be divided into the following functional classes: 1) core and cladding optical materials for transmission of the light signal, 2) fiber coatings to protect and buffer the interior from hostile environments and rough handling, 3) strength-bearing materials of high modulus both to minimize tensile stresses applied to optical fibers and to provide crush resistance, 4) cable filler materials to provide further cushioning and prevention of cable collapse, and 5) protective jacketing which possesses abrasion resistance, chemical resistance, high impermeability to water, flexibility and any other properties which might be required. While much of the information on fiber design and specific materials is not immediately released by manufacturers because of its proprietary nature, we believe that the following summary accurately describes the state of the art materials employed in optical fibers and cables.

3.1.1 Optical Materials

Fiber waveguides presently are fabricated from either silicate glasses, polymers or combinations of both. The specific materials chosen are dictated by a systems optical requirements such as attenuation, NA, dispersion, coupling efficiency and operational wavelength. Low loss materials (losses less than 20 db/km) are normally prepared

by chemical vapor deposition (CVD) of gases to produce low loss fused silicas and doped silicas. Moderate loss materials (20-100 db/km) are typically less pure silicas and crucible melted,high purity silicate glasses. High loss materials (loss > 100 db/km) consist primarily of commercial lead silicate glasses and various types of plastics. The most widely used optical materials are listed in Table 3-1 on page 5.

3.1.2 Coatings and Buffers

A variety of coatings and buffers have been utilized for optical fibers in recent years. In-line dip coating and extrusion of protective layers onto freshly drawn fibers is essential if high strengths and low optical losses are to be maintained. The principal considerations in choosing a coating include good abrasion resistance, impermeability to moisture, reduction of cross talk, chemical inertness, flexibility, low modulus, and compatibility with cable manufacturing. Often more than one protective layer is employed. Typically a thin,dip-coated layer of a few microns is applied immediately as the fiber emerges from the furnace or torch, and this is in turn overcoated with a thicker,more rigid extruded plastic jacket. The most common fiber coatings are listed in Table 3-2 on page 6.

3.1.3 High Strength-Low Strain Materials for Cabling

Theoretically most fiber optic glasses should possess high intrinsic tensile strengths in the neighborhood 3×10^6 psi. Normally such high levels are rarely approached in practical systems. However, it is in the fiber geometry that glasses have exhibited their highest experimentally measured strengths. As-drawn fiber strengths in short gauge lengths presently exceed 10^6 psi in the best fibers. However, as the fiber lengths increase to the km range, strengths fall to the range of 10^5 psi or lower since the probability of finding a weak flaw increases with increasing length. Failure almost always iniates at a surface defect. Even more serious is the further fatigue which can take place in initial fiber strengths, when both applied stress and moisture are present. It is therefore essential to provide strength members in most fiber cables to minimize the loading that the optical fibers receive. Ideally, such strengthening materials have both high tensile strength and high Young's modulus (i.e. they must exhibit very little elongation under applied stress). To achieve flexibility, strength members are normally employed in the form of multifilament yarns rather than as solid rods or heavy gauge wires. Both metallic and dielectric strength members have been employed. The most common materials used to date have been Kevlar 49 (low strain), Kevlar 29 (high tensile stress)

TABLE 3-1. TYPICAL OPTICAL FIBER CORE AND CLADDING MATERIALS

Material	Use	Method of Preparation	Type of Fiber	Principal Mfg.
SiO_2	Core or Cladding	CVD ($SiCl_4$)	Low loss step index	Corning Bell Labs Heraus Schott (Suprasil) Thermal Syndicate (Spectrosil)
SiO_2-GeO_2	Core	CVD ($SiCl_4$, $GeCl_4$)	Low loss step-graded index	Corning ITT Bell Northern
SiO_2-B_2O_3	Cladding	CVD ($SiCl_4$, BCl_3)	Low loss step index	Bell Laboratories
SiO_2-B_2O_3-GeO_2	Core or cladding	CVD ($SiCl_4$,BCl_3,$GeCl_4$)	Low loss graded index	Bell Laboratories
Alkali borosilicate	Core or cladding	crucible	Low loss step index	STL British Post Office
SiO_2-TiO_2	Core	CVD	Low loss step index	Corning
Lead silicate	Core	Crucible	Moderate loss step index	Pilkington (Galileo)
Lead silicate (F2)	Core	Crucible	High loss step index	Schott (Corning, Galileo Valtec, AO)
RTV silicones	Cladding	Polymer	Low to moderate loss step index	Dow Corning GE, Shinetsu
Polymethyl methacrylate	Core	Polymer (PMMA)	High loss step index	Dupont
Polystyrene	Core	Polymer	High loss step index	Dupont

TABLE 3-2. FIBER COATING AND BUFFER MATERIALS

Material	Application	Type of Material	User	Manufacturer
Kynar	dip coated	polyamide	Corning	Pennwalt
RTV	dip coated	silicone	Bell, ITT	Shinetsu Dow Corning GE
FEP	extruded	Teflon (fluorinated ethylene propylene)	Bell ITT Corning Dupont Valtec Galileo	Dupont
PFA	extruded	Teflon (perfluoroalkoxy side chain)	Bell ITT Dupont Valtec FOC FCI	Dupont
TFE	extruded	Teflon Terafluroethylene		Dupont
EVA	extruded	ethylene vinyl acetate (Alathon 3170)	Corning	Dupont
Estane	extruded	polyurethane	ITT	Dupont
Roylar	extruded	polyurethane	ITT	Dupont
Aluminum (other metals)	dip coated	metal	Hughes	---

and steel (low strain, high tensile stress). Additional possibilities include S glass fibers, boron fibers, sapphire fibers (NAFI patent) and graphite fibers. The actual choice depends on the specific application being considered.

YOUNG'S MODULUS OF TYPICAL STRENGTHENING MATERIALS

S Glass	10^7 psi
Kevlar 49	1.9×10^7 psi
Steel	3×10^7 psi
Carbon	5×10^7 psi

3.1.4 Cable Filling Materials

Optical cable design and manufacture have only a short history but are rapidly becoming rather sophisticated. Cable filling materials have been introduced to provide a variety of requirements including 1) additional buffering to minimize lateral deformation of the fibers which can produce breakage or additional optical losses, 2) prevention of cable kinking under bending and torsion stresses, 3) provision for fiber slippage within cable during bending to prevent high local tensile stresses, 4) prevention of cable collapse under high hydrostatic pressures incurred during undersea applications, 5) provision for further optical isolation of neighboring fibers for very low cross-talk requirements, and 6) prevention of moisture buildup in the vicinity of the optical fibers. Typical fillers presently being used include expoxies, paper tapes, glass yarns, cotton, plastic sheaths and spacers, polyster and teflon tapes, metal tubes, kevlar yarn and polyethylene greases. It is expected that this list will grow rapidly as experience with fiber optic cables increases.

3.1.5 Fiber Sheathing and Jacketing Materials

Sheathing for fiber cables should possess flexibility, crush and impact resistance, temperature stability, low friction, chemical inertness and water impermeability. For the most part, sheathing and jacketing materials for both fiber bundles and cables have been assorted plastics and polymers. These include polyvinyl chloride (PVC), polyethylene, various teflons, nylon, hytrel and polyurethanes. A tradeoff between rigidity to minimize stress induced optical losses and flexibility to permit winding and coiling is normally required.

3.1.6 Fiber Materials Efforts Within the Navy

NRL has the capability to prepare and characterize and draw fiber optic grade glasses. A current NRL program is directed at the development of moderate loss (100 db/km), high NA, radiation-resistant glasses for fiber applications. Polymer coatings for fibers are also being studied. Most other materials work is performed on a contract basis by industry via NELC programs.

3.1.7 Some Present Fiber Materials Needs

a) Intrinsic optical losses of synthetic silicas must be reduced to consistently fall below the 2-3 db/km level needed for long distance links with a minimum of repeaters.

b) Higher NA CVD fiber materials must be developed to help reduce microbending losses.

c) The presently high loss plastic fibers should be improved to the 100 db/km level for avionic, missile, satellite and shipboard applications.

d) Radiation resistant fiber materials must be developed to take advantage of the EMP immunity offered by dielectric fibers.

e) Higher strength glasses must be developed and failure mechanisms identified.

f) High NA silicate glasses and silicate glasses in general should be developed with optical losses in the 50-100 db/km range for fiber databus applications.

g) Fiber coatings and buffers must be further evaluated on the basis of minimum damage of the fibers, maintenance of high strength, ease of application, impermeability to water, minimum stress-induced optical loss, uniformity of application, thermal coefficient of expansion, abrasion resistance, durability, chemical inertness, etc.

h) Jacketing materials must be improved against damage due to high temperatures and rough handling.

These needs can be summarized briefly by stating that lower optical losses and higher strengths must be obtained and then maintained under actual conditions.

3.2 Optical Fibers

Present day optic waveguides can be grouped into four general classes: 1) low loss, low NA synthetic silica and doped-silica fibers with either step or graded index, 2) moderate-to-high loss complex silicate glasses of moderate to high NA with step or graded index, 3) high loss, high to moderate NA, step-index plastic fibers, and 4) low to moderate loss, moderate NA, polymer-clad fused silica step-index fibers. Table 3-3 contains a listing of many common fibers and their characteristics.

3.2.1 Synthetic Silica Fibers

These fibers are prepared by CVD processes which are responsible for their ultrahigh purity, homogeneity and low optical losses. Bell Labs have recently reported losses of 0.9 db/km and Japanese workers 0.5 db/km in these types of fibers. The three principal manufacturers of low loss fibers in the U.S. are Corning, ITT and Bell Laboratories. Corning and ITT fibers typically have Ge-doped SiO_2 cores with SiO_2 claddings whereas Bell Labs uses both SiO_2 cores with B_2O_3-SiO_2 claddings and a GeO_2-SiO_2-B_2O_3 graded fiber with SiO_2 outer layer. Because the preforms for these fibers are formed layer by layer, the processing can be controlled to produce a graded index across the diameter by varying the GeO_2 concentrations of each layer. Mode dispersions of less than 0.5 nsec/km have been achieved by both Bell and Corning. These fibers are the most attractive for long distance, high data rate applications and have received the greatest attention in the optical fiber R&D efforts throughout the world. Strengths as high as 900,000 psi have been reported for short lengths of these fibers by Bell Labs, ITT and Fujikura of Japan. In km lengths fibers have survived 100,000 psi proof testing at ITT.

Corning presently offers a range of 10 graded and step index types of low loss fibers (EVA Buffered Coreguide Fibers) with NA's of 0.16 to 0.20, maximum losses of 3 db/km at 820 nm and bandwidths as high as 1 GHz at 1 km lengths. Typical diameters are 5 mils (125μ). Environmental testing of these fibers has included exposure to 90% humidity, immersion in distilled, stagnant and salt water, temperature cycling between -50^{o}C to 70^{o}C, proof testing to 25,000 psi in km lengths and exposure to isostatic pressures of up to 20,000 psi. All of the above tests have failed to produce any significant degradation in the fibers. The low NA of the Corning fibers makes them susceptible to microbending loss unless well buffered as was learned with the NELC undersea tow cable program. The strengths of Corning fibers seem to be substantially lower than those achieved by ITT and Bell Laboratories.

TABLE 3-3. PROPERTIES OF TYPICAL OPTICAL FIBERS

Fiber Type	Mfg.	Core	Cladding	NA	Loss (.85μ)	Profile	Cost/m
Coreguide	Corning	SiO_2-GeO_2	SiO_2	.18	3-10(db/km)	step or graded	\$1-\$5
GS-02-10	ITT	SiO_2-GeO_2	SiO_2	.25	4-12	step	\$3
BTL-X1*	Bell Labs	SiO_2	SiO_2-B_2O_3	.15	1-5	step	---
BTL-X2*	Bell Labs	SiO_2-GeO_2	B_2O_3	.3	1-5	graded	---
S-10	FCI	SiO_2	SiO_2-B_2O_3	.25	10	step	\$4
Quartzwire	FOC	SiO_2	plastic	.25	20	step	\$1.65
Low-loss	VALTEC	SiO_2	plastic	.22	40	step	\$2
PS-50H	ITT	SiO_2	silicone	.25	$<$ 50	step	---
HYTRAN	Pilkington	Pb glass	borosilicate	.50	80	step	\$3
(5010, K2K 101, LGM)	Numerous	Pb glass	borosilicate	.60	800	step	\$.25
Crofon	Dupont	PMMA	EVA	.53	2000	step	\$.05
PFX-0715†	Dupont	PMMA	EVA	.53	1000	step	\$3

*These designations are the author's for experimental Bell Fibers.

†Plastic fibers have their lowest losses in the visible, this one being 470 db/km at .67 μ.

3.2.2 Polymer Clad Silica Fibers

The preparation of the graded index,low loss fibers by CVD techniques requires sophisticated experimental techniques and analytical facilities that make it difficult for small companies or laboratories to compete or mount a state-of-the-art program. However,synthetic silica rods of high purity are available from Amersil (Suprasil) and Thermal American Fused Quartz (Spectrosil) which have optical losses as low as a few db/km. By use of a torch, laser or high temperature furnace, these rods can be drawn into high quality,low loss fibers. The fibers can be immediately dip-coated in a plastic or silicone solution and receive an in-line extrusion of a thick protective polymer jacket such as the FEP, PFA or EVA materials listed in Table 3-2. Depending on the silica core material used, losses as low as 10 db/km have been achieved through the use of special low-loss silicone claddings manufactured by Shinetsu of Japan.

This relatively new type of fiber is durable, quite strong and lower in cost than the CVD fibers. It is therefore attractive for a wide range of military applications including avionic systems, medium distance land lines such as Army front command posts, shipboard data transmission and torpedo guidance cables. Polymer clad silica fibers are now available from a number of suppliers including ITT, Valtec, Dupont and Schott.

3.2.3 Complex Silicate Glasses

Virtually all of the early glass fiber-optic bundles available since the mid 1960's have been fabricated using lead silicate glass cores and borosilicate or soda-lime silicate glass cladding, the lead being added to produce a high index of refraction. The high indices of lead glasses give these fibers a high NA, permitting the use of very thin cladding layers since the internal reflection process is very efficient. Although the optical losses of these fibers tend to be high due to the use of commercial grade materials (between 300 to 1000 db/km), coupling is extremely efficient to both conventional light sources such as LED's and to the T couplers used in multiterminal networks. In short-run applications such as the A-7 in which cable losses are insignificant, lead silicate fibers were chosen because of their attractive coupling features. Most of the companies drawing this type of fiber in the U.S. including Corning, Galileo, Valtec, Bausch and Lomb and American Optical have employed a Schott glass (designation F2) prepared in Germany as the fiber core glass rather than undertake their own research programs. Pilkington Bros. of England have succeeded in

reducing the losses at 0.85μ of a lead silicate fiber below 100 db/km in a fiber marketed under the trade name Hytran. Galileo is licensed to market Pilkington fibers in this country. One severe drawback of lead silicate fibers is their extreme sensitivity to ionizing radiation as discussed in Section 3.2.2.

Other types of silicate glass optical fibers are also available,although less common. The British Post Office and Standard Telecommunications Laboratories have successfully drawn alkali borosilicate glass fibers with losses below 5 db/km. The Japanese Selfoc fibers (graded index) are prepared from a thallium alkali borosilicate glass. Zinc silicate, barium silicate and lanthanum silicate fibers are available. NRL is working on the latter class to develop a high NA radiation hard replacement for the lead silicate fibers.

3.2.4 All Plastic Fibers

Plastic fibers are normally fabricated from polymethylmethacrylate (PMMA) and polystyrene. Dupont has been marketing high loss Crofon fibers for many years and these have seen use for short runs in automobiles and in medical fiber scopes. Other smaller companies in the field include Poly Optics and International Fiber Optics. Although losses are presently high in plastic fibers, there is a good possibility of reducing attenuations perhaps to the 100 db/km level or lower at certain selected wavelengths. The current high losses in plastic fibers do not arise because of high intrinsic absorption, but rather because of very high scattering losses due both to unwanted suspended particles and high interface losses. Plastic fibers offer excellent mechanical properties near room temperature and do not suffer the brittle fracture problems of the glasses. The best plastic fiber currently on the market is the Dupont PFX-0715 with a loss of 470 db/km at 670 nm. Absorption in the 0.8 to 1.0μ range tends to be quite high because of vibrational overtones of the C-H stretching bands in the plastic. Silicone type materials or other more exotic polymers may eventually offer better transmission in this region and should be investigated. These types may also hold the promise of higher temperature stability. There has been essentially no funding of plastic fiber optic materials by the Navy to date. The good radiation resistance, light weight, mechanical flexibility and breakage resistance of plastics makes them attractive for many short run applications. The development of lower optical losses and better thermal stability would greatly extend their usefulness in Navy systems.

3.3 PROBLEM AREAS IN OPTICAL FIBERS

Two specific areas which need to be addressed by the military programs geared to fiber waveguides relate to the strength of fibers and their radiation resistance. While the first of these areas is of universal concern to all users and manufacturers and has been receiving a great deal of attention worldwide, the second is primarily a military problem and cannot be expected to receive much in the way of spin-off from industrial research programs.

3.3.1 Strength of Optical Fibers

The mechanical properties of glasses have been studied for many years and are well characterized. Most work, however,has been conducted on bulk specimens,although investigations on silica, S glass and E glass (the latter two being special glass compositions used for commercial non-optical fiberglass applications) fibers have been reported.

Failure of glass under tensile stress results from the presence or introduction of flaws or microcracks on the surface. Under tensile loading, the stress at the crack tip increases many times over the value of the externally applied stress because of the leverage introduced by the long,thin crack geometry. The bonding strengths ($\approx 3 \times 10^6$ psi) of the material are exceeded and the crack propagates inward, resulting in failure. Crack velocity in any given material varies with applied stress and environmental conditions such as temperature and relative humidity. Failure is further complicated by the chemistry at the crack tip, since the presence of water helps to reduce the strength of the Si-O bonds resulting in sharply reduced strengths. All of these factors are important when considering the development of high strength fibers. The keys are to achieve a flaw-free fiber surface, to maintain it by suitable coatings that provide mechanical protection and to exclude as best as one can the presence of water or water vapor from the fiber surface. An alternate approach which should also be considered is the feasibility of the surface compression strengthening of fibers. A compressive stress on the glass surface offsets applied tensile stresses so that the crack tip stress is greatly reduced or eliminated.

The mechanical integrity and environmental degradation of optical fibers is one of the major problems facing the technology at the present time but substantial progress has been made during the past year. In the past few weeks, the author has spoken to scientists engaged in strength research on optical fibers at Bell Labs (Chuck Kurkjian),

Corning Glass (Bob Maurer and Don Keck) and ITT (Mokthar Maklad) in order to determine both the progress and the direction of their programs on mechanical properties of fibers. Dick Eastley and Don Albares of NELC, Rod Katz of NAFI and Roy Rice of NRL were also contacted with regard to discussion of fiber strengths. This included a review of the undersea cable program and of the meeting on Strong Optical Fibers sponsored by ARPA on July 21-22 at La Jolla, California, a summary of the NELC Optical Fiber Strength Improvement Plan, and an outline of the two new programs recently initiated by ARPA at ITT and Hughes for development of high strength fibers. With all of this information in hand, we will attempt to summarize the present situation which the Navy faces with regard to strength related failures of fiber optic systems.

It is important to determine the present level of tensile strengths being obtained in the better fiber laboratories. In May 1976, Bell Labs (Kurkjian and coworkers) reported tensile strength measurements on fibers of lengths up to 50 m gauge lengths. Average strengths were 700,000 psi for 10 m lengths, 200,000 psi for 50 m lengths and 64,000 psi for 1 km lengths. As of 1 August, 1976 these levels have now increased to over 1,000,000 psi at 10 m, 500,000 psi at 50 m lengths and well over 100,000 psi at 1 km lengths. This dramatic increase in strength has been achieved on furnace-drawn silica fibers that have been coated with a UV-cured epoxy-acrylate, employing a compliant applicator. In addition to the new non-damaging coating process, Bell work indicates that the use of high quality starting materials, cleanliness in the drawing process and care of preform handling are important. In a publication to appear in late 1976, Kurkjian has demonstrated that experimental data gathered on 20 m gauge lengths of the Bell fibers were sufficiently accurate to permit extrapolation of strengths for multikilometer lengths. The Bell-Norcross, Georgia Lab has proof tested upwards of 200 km of fiber and compared this favorably to tensile test data on short lengths of comparable fibers. Theoretical studies are also being conducted to determine the limitations of the Weibull statistical analysis approach which is being used by most laboratories to predict strengths at long lengths based on experimental measurements at much shorter lengths. It also is my impression that actual strength values of Bell fibers may already be well in excess of the released figures. In any case, a substantial effort to upgrade fiber strengths is underway at Bell Labs, and if past performance is any guide, many of the solutions to the Navy fiber strength problems will come from this effort.

The advances in strength of fibers during the past six months have not been confined solely to Bell Labs.

ITT has achieved good results with their silicone dip-coated and teflon-extruded jacketing of silica fibers. Results of tests on 2 plastic-clad silica (T08 material) fibers with silicone RTV claddings were quoted to the author by Dr. Maklad of the Roanoke Lab. 1 km lengths are now routinely proof tested by ITT at 100,000 psi prior to cabling. Experimental data taken from 40 specimens of 60 cm gauge lengths of the T08 fiber were as follows: Fiber 1, minimum breaking stress 840,000 psi, maximum breaking stress 2,361,000 psi, average breaking stress 1,273,000 psi. Fiber 2, minimum breaking stress, 649,000 psi, maximum breaking stress 2,785,000 psi, average breaking stress 1,588,000 psi. These values are probably high because of the insufficient number of samples tested but the strengths are still impressive. This type of fiber has been drawn through conduits at NRL in lengths of 100 meters for radiation experiments and proved to be the strongest fiber which we have ever tested. Strength has been attributed largely to the immediate dip-coating of the fire-polished fiber and the in-line extrusion of the protective plastic jacket. ITT has just received a ARPA contract to further explore other types of polymer coatings for the purpose of further increasing strengths.

Corning has not thus far been able to achieve strengths as high as those of ITT and Bell. However, Corning has always tended to delay publication of important advances until all associated patent work is completed. Corguide low loss fibers are proof tested at only 25,000 psi and in a few instances have successfully passed 50,000 psi in km lengths. Bob Maurer indicated that as many as 30 process control parameters have been identified which affect the as-drawn strengths, with in-line coating, preform cleanliness and surface condition, dust count, drawing rate and material homogeneity being among them. Failure prediction studies are also being pursued with a paper on the subject scheduled to appear this fall in the Journal of Applied Physics coauthored by Maurer and R. Olshansky. Corning has also gone to routine testing of 20 m gauge lengths vs the original 0.6 m lengths reported on last year and is now able to predict failure strengths at longer lengths quite well provided an adequate number of samples are tested.

Elsewhere in the world, both Hitachi Cable and Fujikura Cable Works of Japan have reported tensile strengths of low loss silica fibers in the range of 950,000 psi, fiber drawing conditions and the application of the first thin coating on the fibers being cited as the key factors. Fiber strength work is also being conducted by Fort, CNET and Thompson CSF in France, Pilkington, STL and the British Post Office in Britain, Siemens AG in Germany, Philips in the Netherlands and numerous other

Japanese companies including Toshiba, Nippon Electric, Sumitomo and NTT.

The judgement of most researchers contacted during the past few weeks was that strengths of 250,000 psi were probably attainable in the next year in lengths of several km and that ultimate strengths will be much higher. This corresponds to elongations of 2.5% in fused silica. The so called "strength problem" of fibers is well on its way to being solved. The use of polymer coatings has also paid a dividend in the stress optic-microbending area, since cabling losses now amount to only a few db/km in the latest cables being fabricated. The use of slightly higher NA fibers (.3 vs .18) prepared by CVD techniques is expected to further reduce these losses, as is the use of smaller core diameters.

One problem which remains unsolved at the present time, in addition to further enhancement of as-drawn strengths, is the static fatigue of glass fibers after deployment due to stress corrosion from the migration of water through the polymer coatings to the fiber interface. As a rule of thumb, experienced glass technologists have always used a value of about 1/4 the proof test stress as an operational stress with zero probability of failure under worst conditions. This margin was built in to take into account static and dynamic fatigue effects which invariably would occur. For a given material strength, delayed failure can be eliminated by excluding water from the surface or by offsetting tensile stresses by compressional surface stresses. The polymer coatings, while resisting water permeation, will permit passage after exposures of a few months. A different coating approach to exclude water is being pursued by Hughes Research Labs, Malibu, California under a recent contract let by ARPA. Metallic coatings beginning with aluminum are being tested as the primary coating material for optical fibers. This should exclude water but may possibly inflict damage on the surface during the high temperature deposition. Hughes already has preliminary evidence on hand suggesting there is some merit in the process for reducing stress corrosion effects.

Another advance has also been made by the drawing up of a standardized set of environmental tests by a working group of the Society of Automotive Engineers (SAE). These will serve as the basis of a qualified Mil-Spec for optical fiber cables and connectors. Bob Lebduska of NELC was a member of the SAE panel. There is also a Tri-Service Committee that has been concerned with outlining specifications and testing procedures for fiber optic components.

As discussed in Section 4.2.1 of this report, the worst case facing the Navy in the area of fiber cable strength is the towed array cable, which is expected to undergo elongations of a few percent during operation and sustain loads in excess of 30,000 lbs. This requires fiber strengths of 100,000 to 200,000 psi in the 10 km gauge lengths for typical operational periods of 5 to 7 years. By the helical winding of fibers around the steel strength member, perhaps a 0.5% elongation of the fiber can be eliminated. This implies then a worst case elongation of 1.5% or 150,000 psi. Factoring in the expected static fatigue due to stress corrosion, initial drawing strengths of 500,000 psi are needed. While not possible today, the level of effort being focused on the strength problem throughout the world suggests that even this worst case application is well within reach. Most other less demanding Navy applications should be virtually out of danger from tensile failure in the next year as 250,000 psi as-drawn strengths are approached. This optimism is reflected by most scientists in the fiber field. Bell Labs currently is projecting 1981 as the year for initiation of large scale fiber communication cable installation with 20 year lifetimes. Military systems may well see large scale production in about the same time frame but with specific applications well in advance of this.

3.3.2 Radiation Effects in Optical Fibers

Dielectric glass or plastic cables are particularly useful in nuclear environments because of their immunity to electromagnetic pulse (EMP) effects. However, it is now recognized that many existing fiber-optic cables suffer substantial losses in optical transmission when subjected to ionizing or nuclear radiation. The major problems which arise are associated with light-absorbing and light-emitting defect centers produced by the impinging radiation in the fiber waveguide itself. Because of the very long optical path length present in a typical fiber-optic system, substantial losses can result in the presence of relatively low radiation levels.

NRL scientists were among the first to recognize and to measure the sensitivity of fiber optics to ionizing radiation. The damage mechanisms in the irradiated fibers have been identified, and a program is focusing on the development of more radiation-resistant fiber materials. NRL presently has the capability both to prepare and characterize high-purity, fiber-optic grade glasses and to draw these into optical fibers of more than 1-km lengths. Special emphasis is placed on the development of suitable fibers for near-term Navy systems such as the A-7 and P-3 aircraft. Close cooperation is maintained

with the Naval Electronics Laboratory Center (NELC), which has the broad responsibility to implement the fiber-optic technology presently being developed.

High purity fused silica is recognized as an extremely radiation resistant optical material. However recent tests of a fused-silica-core,polymer-clad fiber performed at NRL for Army ECOM in June,1976 have shown unacceptable radiation damage at the 100 rad level. This Army cable was to have been hardened to the 10^5 rad level. The lead silicate type fibers presently being used in the A-7 demonstration cannot tolerate more than a few rads of irradiation without sustaining damage. NRL has put this effect to good use by designing a real-time fiber optic dosimeter with an LED source and Si photodetector. Radiation hardening is also essential for the fiber optic data bus and cables being considered for advanced long range missiles such as Trident and MX. Remote inspection of nuclear reactor compartments of Navy submarines also requires utilization of radiation hard fibers.

All three services have radiation hardening needs so that a Tri-Service Radiation Effects Working Group has been established to coordinate and address these needs. These hardening requirements extend to all components of the fiber optic systems, not just cables. Details of the radiation effects in fibers can be found in the references cited in Section 7.8 of the Bibliography.

3.4 FIBER OPTIC CABLES

The simplest type of fiber cable is the bundle in which anywhere from a half dozen to many hundreds of fibers are jacketed in a plastic sheath, with terminations being made on either end using epoxies, metal ferrules and conventional glass polishing techniques. Most of the fiber wiring used in both military and domestic systems up to the present time has employed this approach. Because of the redundancy offered by the bundle approach, the mechanical reliability of the fiber link could be maintained in spite of the breakage of a large fraction of the fibers. Butt coupling of high NA fiber bundles to sources detectors, mixing rods and to one another has also proved to be straightforward and effective. Many future systems will no doubt continue to utilize this approach. However, as the probability of mechanical failure diminishes and more expensive, sophisticated,high-bandwidth,graded index fibers emerge, as core-clad ratios decrease and buffer layers increase in thickness and as narrow-beam,high-intensity injection lasers come on line in optical communication systems, it is evident that single fiber technology will emerge as the replacement for many of the bundle systems. This trend is already seen in the long

distance cables designed for undersea links, for Army communications and for the Bell Telephone-Atlanta system. In the latter case, a cable was designed employing 144 fibers in a rectangular array,each with a discrete position so that it is operated as an independent channel. Operating at a 44.7 Mb/s data rate,the Bell-Atlanta cable can carry the equivalent of 48,000 simultaneous telephone conversations. Average loss of the cable in place was 6 db/km over a distance of 10.9 km. Over 18 low loss splices were used in the repeaterless link. Fiber alignment and connector design are crucial for low loss coupling on a fiber-to-fiber basis,but Bell losses typically run less than 0.2 db per fiber splice. It is the belief of this author that the Navy should be undertaking a larger effort in single fiber technology while maintaining and upgrading the bundle approach.

Cable design depends greatly on application. End-loaded cables such as sonobuoy or tow types require different designs from pole-mounted cables strung as conventional phone lines. Ducted cable must undergo severe installation stresses but is essentially unstressed or lightly stressed during subsequent operation. In practice, cable designs become quite complex and will not be described here although Section 3.1 provides detailed information on the five classes of materials and basic concepts involved in cable construction. Some important cable properties normally desired include 1) adequate buffering to minimize stress-induced optical losses, 2) high tensile strength, 3) resistance to water vapor penetration, 4) thermal stability over operational temperatures, 5) cold bend flexibility, 6) chemical resistance, 7) crush or impact resistance, 8) controlled bend diameter, 9) ease of termination, 10) ease of installation, 11) low maintenance, and 12) reasonable cost.

Specific cable designs for a wide number of applications are contained in the References listed in Sections 7.6 and 7.9 of this report. Details of first generation tow, sonobuoy and torpedo guidance cables are discussed in Section 4.2 on undersea applications.

4.0 NAVAL SYSTEMS APPLICATIONS PRESENTLY UNDER DEVELOPMENT

It is impossible to provide an in depth analysis of all the Navy systems presently being considered for fiber optic links. In general, it is possible to divide the applications into four general categories: airborne, undersea, shipboard and land based platforms with the last category being more pertinent for Army and Marine Corps operations. We have attempted to describe some of the key programs in each of the first three categories in the sections that follow.

4.1 Airborne Platforms

The area of avionics data transfer is considered to be the first military application which is likely to be impacted by fiber optic technology. Distances are short and the environmental conditions are favorable so that off-the-shelf components would seem to be capable of doing the job, today. Candidate platforms for fiber systems are high performance and surveillance aircraft such as fighters, VSTOL aircraft, reconnaissance and antisubmarine aircraft. Several types of fiber replacements are possible with the easiest being a simple one for one substitution. The most effective approach, however, is to use either time, frequency or space multiplexing to reduce the number of cables required. The ultimate airborne fiber system is expected to use data bus (multiterminal) multiplexing in which a single high capacity fiber transmission line carries many different multiplexed signals and is linked to a number of spatially distributed terminals. The fiber data bus does not experience the coaxial cable data bus problems of reflections, ringing, cross talk, EMI, ground level voltage shifts, sparking and low bandwidth. Details of the fiber databus work at NELC and NRL can be found in the references given in Section 7.9 of this report.

Two of the first aircraft to serve as candidate platforms for fiber systems have been the A-7 high performance fighter and the P-3C antisubmarine aircraft, the former actually being used as a field demonstration for fiber systems. Details of these two programs are given in Sections 4.1.1 and 4.1.2 respectively.

4.1.1 A-7 Airborne Light Optical Fiber Technology (ALOFT) Demonstration

The purpose of this program was to bring optical fibers out of the laboratory into a real Navy platform and to demonstrate that fiber optic technology at its present level is sufficiently advanced to be used for internal aircraft data signal transmissions. Initial project funding was received by NELC from NAVAIR in March 1974. During the spring of 1976, successful flight tests were performed at NWC, China Lake, climaxing in a bombing and rocket firing demonstration during May.

IBM was granted the contract to build an interface system in the A-7 aircraft with multimode fiber optic point-to-point connections for the integrated navigation and weapons delivery system, linking the A-7 tactical computer and peripheral avionics units. The demonstration of the fiber optic signal multiplexing system was conducted in three stages: 1) laboratory simulation, 2) ground flight simulator testing, and 3) a full flight test and evaluation. IBM Federal Systems Division, Oswego, N.Y. delivered the A-7 ALOFT system hardware to NELC in October 1975. This consisted of 13 fiber optic cables and associated electronic multiplexing circuits and fiber interface circuits external to the existing avionics. The data rate maximum for the system was 10 M bits/sec. This replaced an extremely complex wire system carryiny 115 signals, consisting of twisted pair, three-wire and coaxial cables.

In this program LTV, Dallas, Texas designed the installation plan to integrate the IBM hardware into an A-7 for a Navy flight test and evaluation and were responsible for a three month ground test during the installation of the hardware in an avionics simulator of the A-7 N/WDS. The Navy software used in the demonstration was developed by NWC, China Lake. The Naval Air Test Center, Patuxent River, Md. is currently supporting the project via work being conducted by the Reliability and Maintainability Branch.

An interim progress report of the A-7 ALOFT Demonstration covering the period from March 1974 through December 1975 was issued on January 1, 1976 (NELC Technical Report 1968, LCDR J.R. Ellis, USN). A final report will appear in the fall of this year. Numerous other reports on the program are also available from NELC.

Analysis

The question which now must be asked is not whether or not the A-7 demonstration was a success but rather "What is the near term role of fiber optics in avionic systems?". What are the present requirements driving the fiber optic technology? NELC has shown that substantial reductions in weight and size are possible. Critics have countered that a multiplexed fiber system is being compared to non-multiplexed wire system. This is certainly true, but we should be quick to point out that the freedom from ground loops, the low cross talk and the much greater bandwidth make multiplexing possible with optical fibers and difficult or impossible with the all wire system. While these weight and size savings are desireable, the major payoff for avionic systems using fiber optics comes in the area of electromagnetic compatibility. This should result in sub-

stantial cost savings in the design and test stage of advanced aircraft. The increasing use of nonmetallic composites in aircraft also makes RFI and EMI immunity more crucial to performance. The high bandwidth offered by fibers must not be discounted simply because present day aircraft lack high frequency systems. Fiber bandwidths permit the use of serial rather than parallel transmission techniques. There is also the trend toward expanding display technology requiring wider bandwidth systems. The need therefore exists.

The major stumbling block at present is the lack of military-qualified components for fiber optic systems. The Tri-Service FO Committee has recognized this problem. Specifications have been drawn up for testing of FO components. NELC and NAFI have joined together to draw up a Manufacturing and Technology program for avionic applications. Standardization of fiber cables and connectors is being encouraged. Second generation, minaturized, ruggedized,wider-bandwidth source and detector modules are being procured. Cost, reliability, and failure analysis studies of all components are being pursued. These efforts will take further time and money in the 6.2 area. However the potential savings arising from solution of electromagnetic compatibility problems alone would seem to warrant a greater outlay of funds than is presently available. At the present rate of development, these fiber systems will probably not see large scale deployment until the early 1980's, and perhaps later. This is my best judgement as a scientific investigator in the fiber optic area and is not based on any exhaustive study of the pace of development of FO components. However, as with all new technologies it takes time to establish reliability and credibility with designers, manufacturers and users. In particular,the possible ageing process of fiber cables due to stress corrosion remains to be investigated in long term studies of field deployed demonstration systems such as the A-7. Reliability of other components not discussed here such as light sources, connectors and couplers must also be improved.

4.1.2 P-3C Aircraft

An advanced Navy P-3C aircraft weapon system (PROTEUS) with a fiber optic interface is a potential candidate for the first actually deployed fiber optic avionic system. Areas of interest on the P-3 for fiber application include a 10 MHz intercomputer channel, a 10 Hz to 30 MHz video channel and a 8 Hz to 40 kHz acoustical channel with a 48 db dynamic range. Gary Averill and T.R. Trilling at the Naval Air Development Center, Warminster, Pa. are responsible for the program and Lockheed, California of Burbank have designed the system (M.K, Zaman and D.J. Oda). Lockheed has configured and evaluated a fiber optic transfer

link in the P-3C integration test facility at Burbank. The fiber link was substituted for the existing wire links between the Univac CP-901 computer and a peripheral with totally satisfactory performance.

The P-3 fiber optic system is expected to produce a factor of 10 reduction in weight and a factor of 3 in volume compared to the copper wire system. However, it is again in the electromagnetic compatibility area that the largest payoffs are expected. Electromagnetic cross talk and interference, ground loops, impedance matching, and security problems should be greatly reduced or eliminated entirely. Information transfer on the P-3 involves runs of less than 30 ft and bandwidths of 30 MHz or less so that components from the A-7 program can be used provided that the bandwidth is increased. The present P-3C computer input/output communication is achieved using parallel data transfer over multiwire twisted pair cables. The fiber bandwidth offers the possibility of serial transmission over few cables. Lockheed has successfully developed a fiber optic interface for the P-3 which included the design of external serial to parallel and parallel to serial converters for the 30 bit parallel information links. Galileo fiber optic bundles of lead silicate glasses with losses of 700 db/km were used, similar to the Valtec fibers employed in the A-7. Both of these fibers have been shown by NRL to be unacceptable in operational systems because of extremely high sensitivity to radiation. The P-3 system is being contemplated for FY 1979.

4.2 UNDERSEA APPLICATIONS

Fiber optic technology is also potentially capable of impacting on a wide variety of undersea systems including towed arrays, sonobuoys, bottom laid cables, torpedo guidance, mine countermeasures, RPV's and tethers for various tasks involving search, mapping and inspection. The important advantages here include small size, near neutral buoyancy, high bandwidth, increased range due to low attenuation, low cross talk and the absence of inductive and capacitive effects. The demands on the fiber cable vary widely with the specific application but it is possible to meet most requirements through the use of three basic types of cable designated simply as heavy, medium and light duty undersea cables. Model systems which can respectively be served by these cable types are towed arrays, sonobuoys and torpedos. These three applications are discussed in the following sections.

4.2.1 Towed Array

This application represents by far the worst case faced by fiber optic technology up to the present time. A joint effort at NUC and NELC, funded largely by ARPA in the past, has been

directed at the development of heavy duty fiber optic cables for tow applications. George Wilkins at NUC, Hawaii and Dick Eastley at NELC have been responsible for the program. A cable of this type must be capable of sustaining stresses of 20,000 to 30,000 lb and elongations of 1 to 2%. Optical attenuations as low as 2 db/km are desired in the final cable and bandwidths of about 100 MHz. Lifetimes of 5 to 7 years are required and lengths in excess of 10 km are desired.

These demands are clearly beyond the capability of today's technology but are not out of reach within the next few years. Elongations of 1 to 2% for a silica fiber correspond to tensile stresses of 100,000 to 200,000 psi. Strengths of this magnitude have been reached in the past few months in km lengths on freshly drawn fibers but stress corrosion due to water is expected to degrade long term strengths by about a factor of four. ARPA programs at ITT and Hughes have recently been let to upgrade fiber strengths by the development of better in-line fiber coating techniques, both polymer and metallic. Bell Labs, Corning, European and Japanese fiber producers have similar high strength efforts which should also produce some spin-off for the Navy. Another serious problem is the stress-induced optical losses, generally referred to as microbending, produced in the fiber by the cabling process. Lateral deformation of the fiber causes the light striking the wall of the fiber to exceed the critical angle of reflection and therefore to be ejected from the waveguide. Solutions to this problem include 1) increasing the NA of the fiber permitting it to tolerate higher angular reflections, 2) use of low modulus buffer materials to mechanically isolate the fiber from its environment, 3) careful control of coating thickness and concentricity and application, 4) decrease of the core/cladding ratio of the fiber, i.e., making the cladding thicker relative to the core size, and 5) use of more rigid jacketing materials which do not readily deform under applied lateral stress. Most of the above ideas have only become apparent during the past year and unfortunately were not incorporated into early cable designs. Cabling-induced losses, however, still exist and presently range from 2-5 db/km in well designed cables. For example, in the past few months Bell Labs have placed a 2 db/km fiber in a cable drawn through conduits in Atlanta, Georgia and have sustained an additional 4 db/km loss after installation. Since the Navy goal is 2 db/km cable, further study of this problem is clearly needed. The effect of large hydrostatic pressures on the microbending must also be evaluated. Cable designs must be improved to reduce both lateral and axial stress placed on the fibers.

In order to evaluate fiber performance under actual undersea conditions, NUC has designed two first-generation fiber optic tow cables. Both have now been delivered to NELC and are undergoing laboratory testing. Both fibers are 0.7" O.D. and designed to take 33,000 lbs of stress. High modulus, braided steel strength members are used in both cables to minimize strain.

The first of the tow cables delivered contains 3 step-index Corning low loss fibers with 0.16 NA, 2 copper conductors for A.C. power and an S glass epoxy matrix surrounding the optical fibers. Air Logistics fabricated the S glass matrix and Simplex the final cable. The optical fibers received only a 25,000 psi screen test from Corning. Optical losses in the final cable at 0.82μ increased to 200 db/km vs the original 10 db/km loss prior to cabling. This is clearly unacceptable.

Results on the second tow cable, fabricated by ITT, have been more encouraging. This cable contained 6 fibers centrally located in the cable, 2 graded-index and 4 step-index. The fibers passed a 100,000 psi proof test prior to cabling. Two coaxial conductors were included for power transmission. Stress-induced optical losses at 0.82μ resulted in a 3 db/km increase in the step index fibers (7 db/km → 10 db/km) and a 10 db/km rise in the graded index fibers (5 db/km → 15 db/km). Extensive testing both within the laboratory and at sea are planned for this cable.

Analysis

It is apparent even prior to testing that the strength and attenuation goals originally sought for the first generation two cables will not be met. However testing should nonetheless provide valuable data and insight into the problems to be encountered in actual undersea conditions. The effects of hydrostatic pressures on stress-induced optical losses, the effects of fiber elongation on attenuation and dispersion, stress corrosion effects on long term strength, cable design, the effects of coiling and winding and many unforeseen problems will be encountered during the testing program. In the meantime, fiber strengths are beginning to increase substantially and stress optic effects due to cabling have been greatly reduced. Fiber cabling experiments in the U.S., England, France, Germany and Japan have been successful in actual field operations during the past year. In our view, a balanced Navy program which seeks to upgrade fiber performance and cable design while gaining valuable undersea test data on first generation heavy duty cables, is the most sensible approach. Improvements here will certainly spin off to the many less stringent cable applications being considered by the Navy. Substantial input from non-military programs can also be expected.

4.2.2 Sonobuoy Cable

A joint effort between NELC (contact - Dick Eastley and NADC (contact - R. Hollar) has been established to develop fiber optic cables for sonobuoy applications. The initial range for the first generation cable is 5 km. Specifications call for a 200 lb load capacity. For this application the fiber cable offers the advantage of large bandwidth and extended range without the inductive problems of wires wound on spools and the capacitive changes en-

countered as sea water wets through cable insulation. In addition,the weight per unit length of a fiber cable in water promises to be substantially less than for metallic cables. Since a transceiver buoy is used, the fiber link must be bidirectional. In addition, the cable must be sufficiently flexible to permit winding on spools of a few inches diameter to permit cannister payout from both the submarine and the buoy.

A fiber optic cable for sonobuoy applications has recently been delivered to NELC by ITT. The cable diameter is .058 inches and contains 2 step-index optical fibers coated with fluoropolymer and 2 stranded steel strength members to provide the 200 lb load capacity. Optical losses after cabling were 5 db/km total at 0.82μ compared to 4 db/km loss prior to cabling. The fibers were proof tested to 1% elongation (100,000 psi) prior to cabling by ITT. In order to achieve the 2-way capability in transmission, a 2-fiber design was chosen for this first generation fiber. In subsequent designs only a single fiber will be employed and the cable diameter further reduced. This fiber is currently undergoing optical, strength, pressure and environmental integrity testing at Tension Member Technology (TMT), Long Beach, California. Results are expected by Fall 1976.

Analysis

This fiber demonstration promises to impact on the potential use of optical links for other medium duty applications such as bottom laid surveillance cables, helicopter tow cables and undersea RPV's. Kevlar is a possible substitute for steel as a strength member to provide a lighter, non-metallic, more flexible cable. One area of need for an extended range capability is the development of a pressure tolerant repeater which is readily deployable with cable payout. A program has been proposed by NELC to develop such a ruggedized, sea tolerant repeater with a photo avalanche diode, pulse restoration, receiver automatic gain control and an injection laser diode. A problem arises with regard to the mode of powering such a unit. For bottom-laid heavy and medium duty cables, the best solution appears to be the incorporation of A.C. conductors into the cable. For short term applications such as long distance torpedo guidance cables, the possibility of battery operation for periods of up to a few hours is attractive. In contrast to the towed array problem, the strength and stress optic problems here are not so severe but questions of optical losses of fibers on small diameter spools, fiber payout from a cannister, sea survivability and single fiber bidirectional operation have yet to be seriously addressed. Funding in the 6.2 area on each of these problems is essential for the successful deployment of fiber tethers for sonobuoy applications.

4.2.3 Fiber Guided Torpedo (MARK 48)

All the advantages discussed in the previous section on sonobuoys apply equally well in the case of torpedo guidance. NUSC and NELC have recently initiated a joint program to develop a fiber optic cable for the MARK 48 torpedo. A contract has just been let to ITT for a 40 mil diameter cable capable of sustaining loads up to 45 lb. Two fibers are also employed in this cable although again, the final design will only contain one. Non-metallic strength bearing stranded filaments will be employed, possibly carbon. Delivery is scheduled for late 1976.

Analysis

The absence of inductive and capacitive effects and shorting problems, greater buoyancy, greater bandwidth, smaller size, and lower loss are clear fiber advantages in this application. A deployable,remotely powered repeater system could permit ranges in excess of 50 km. Plastic-coated,high strength silica fibers of only 20 mil total diameter may be sufficient up to 10 km range. Cannister payout and winding of fibers, survivability during payout from the torpedo, optical losses under actual operation, sea survivability, inside vs outside winding, perfect layer winding, perpendicular vs axial payout from spools and underwater payout of fiber in general are areas which remain to be investigated. The prospects for eventual deployment appear excellent based on the success achieved by Optelcom of Gaithersburg, Maryland in an Army program on fiber guided anti-tank missiles. Fiber payouts from cannisters of 3" diameter have gone as high as 300 ft/sec in air. Preliminary payout experiments in water indicate that the basic problem is acceleration of the cable upon initial payout from the torpedo, but this appears solvable. The Optelcom solution to the bidirectional requirement for the cable is to use LED's at both ends in either a detector or source mode depending on the application of a foward or reverse bias to the device. Unfortunately such a LED detector does not at present compare favorably with the gain provided by a silicon detector. We conclude again by pointing out that the problems to be solved are apparent and that development should continue on a broad front on the torpedo guidance system for the MARK 48.

4.3 SHIPBOARD PLATFORMS

Shipboard communications suffer from many of the same problems as those encountered on aircraft. While large surface ships are normally not bothered by cable weight and size, these factors become significant in high performance surface craft such as hydrofoils and air cushion craft. EMI and RFI problems are of concern on most ships,however,so that electromagnetic compatibility again emerges as an important advantage of fiber

systems. Transfer of intelligence data without encryption aboard ship is also possible using fiber cables. Transfer of voice, video and computer data by optical cables has been shown by NELC to be straightforward. NELC installed secure telephone communications on board the flagship USS LITTLE ROCK several years ago. In addition, a closed circuit TV system was successfully demonstrated aboard the USS KITTY HAWK. The latter system employed a 100 m fiber run and wideband FM transmission. The use of multiterminal fiber optic data bus systems employing large numbers of terminals has been proposed. A substantial savings in cost of installation and maintenance is expected here since point-to-point wiring is replaced by many fewer multiplexed fibers.

NELC has undertaken studies of fiber optic installations on other specific shipboard platforms including audio link systems aboard the submarine USS PLUNGER and fiber optic interconnections for the 2000-ton Surface Effects Ship. In addition, NELC is being funded to design, fabricate and install a fiber optic data link to interface the Compartmented Mode Processing System (CMPS). This project is designed to show the feasibility of employing fiber optics for the transfer of high speed digital data as well as video information for intra-ship communications. The fiber optic link will connect several interactive display terminals, teletype-writers and line printers with the CMPS multiplexer unit. The multiplexer permits the bidirectional transfer of information from the Naval Intelligence Processing System (NIPS) computers to various system peripherals. Project Manager is LT W. Gadino, Code 1500, NELC. Another interesting application of fiber optics on submarines has been demonstrated by F. Allard at NUSC, Newport, R.I.

4.3.1 Fiber Optics Sonar Link

NUSC is presently conducting sea trials of a 52 channel analog fiber link for a sonar array mounted in the bow of a fast attack submarine. A 52 channel converter translates electrical output from the sonar array to light signals at the transducer and fm-modulator ends of the cable. The system employs Dupont plastic fibers (PFX-0715) with an attenuation of 470 db/km at the operational wavelength of .67μ. Cross talk rejection is in excess of 100 db. Laboratory tests prior to sea trials have already demonstrated the superior performance of the fiber optic cables over that of the conventional twisted shielded pairs. An even greater payoff is expected by conducting fiber optics through various pressure barriers and thereby interconnecting electronic elements from different inboard compartments as well as outside the hull. The reduction of the number and diameter of hull penetrations could provide a significant saving in cost and weight of submarine pressure hull design. Results of the sea tests are expected in the fall.

4.4 OTHER APPLICATIONS

Other programs worthy of note at NELC include the design of a fiber optic link between the antenna and transceiver of the AN/PPS-18 general battlefield surveillance radar, installation of fiber communication links at the Norad Cheyenne Mountain Complex for Intelligence and Command and Control Functions and NSA sponsored work on Secure and Intrusion Resistant Fiber Communications. NRL has recently designed a fiber optic radiation dosimeter system for the NTS-2 navigational satellite to be launched in December 1976. Other examples exist but most of the major programs have been discussed in the preceding sections. Section 5 discusses some of the future directions and anticipated applications of fiber optic systems for military applications.

5.0 FUTURE DIRECTIONS AND CAPABILITIES

This report has focussed on only one component of the fiber optic communications system, the transmission link, and it is clearly impossible to predict the pace and direction of military fiber systems developments with only one small portion of a rather complex technology. However, it is possible to project ahead the next 3 to 5 years, confining oneself to the cable area only, and deduce, on the basis of the evidence at hand and the rate of present advance, the near term capabilities of fiber optic cables.

It would be presumptuous on the part of this author to outline a detailed Navy R&D program in the Optical Fiber Technology area and this will not be attempted. The Tri-Service Technical Application Area Document on Fiber Optics Communications Technology scheduled for publication in the fall will provide a detailed program for all the services covering cables, sources, detectors, systems and applications. However, it is apparent to most workers involved in military fiber programs that certain general capabilities must be developed if the fiber technology is to continue to move forward in an orderly manner. These include:

1) Tri-Service Cooperation and Planning

2) Standardization of cables, connectors and component packaging

3) Establishment of Mil Specs for all fiber components

4) Increased reliability and lifetime of components

5) Increased ruggedization of components to accelerate transfer from the laboratory into the field

6) Improved reliability prediction and failure analysis methods

7) Cost analysis of fiber systems vs conventional wire links

8) Inventory build-up of qualified off-the-shelf fiber optics components

9) Increased technology transfer to outside users and other Navy Labs

10) Rapid incorporation of spin-off of domestic fiber programs into military systems

11) Improved cable design with fiber stress relief in both transverse and axial directions

12) Continued materials development in all five fiber cable materials areas. (See Section 3.1.7).

The present efforts of the Tri-Service FO Committee to mil-spec, standardize and improve components have been initiated so that the next few years should see the appearance of standardized fiber cables, connectors and associated hardware required for both step index and graded index point-to-point optical links for military systems. Large scale usage will certainly depend on the success of this program.

Fiber waveguide and cable development will be largely driven by non-military programs whose investments in this technology dwarf those of the military. Low optical losses in the 2 db/km range should be routinely available,and costs should come down substantially as volume increases. Single-fiber systems will eventually replace bundles for most applications. Stress-induced optical losses will not exceed 1 db/km in advanced,properly buffered materials. As-drawn strengths of 500,000 psi for long lengths should be achievable permitting 2% elongations with little likelihood of failure. With the exception of the towed array, the use of optical fibers for virtually all military platforms should be practical,and even high strength tow cables seem quite likely.

Extension of the range of fiber links will depend on the development of both deployable,remotely-powered repeaters and pressure-tolerant,cable-powered repeaters for undersea cables. A wide range of undersea tethers should be developed because of the inherent advantages of fiber systems. Lower loss cables may be achievable by the movement of operation to longer wavelengths near 1.2μ,where both scattering, dispersion and intrinsic absorption are lower. This might permit cable losses around 1 db/km or less permitting 50 km repeaterless links. Source and detector work are clearly required if this is to be come a reality.

Both avionic and shipboard fiber data bus multiplexing systems should be developed further. A system demonstration on a Navy platform would be the natural first step, just as the A-7 program served to introduce the general concept of fiber technology. The replacement of expensive, bulky point to point wiring by fiber multiplexing should reap substantial cost savings, increased performance and reliability, and reduced maintenance.

Single-fiber cables plus matching connectors are beginning to appear and should be pursued as a second generation fiber optic technology. Even more advanced are the high bandwidth,single mode fiber systems which can be efficiently coupled to the broadly advancing integrated optics,thin film components. The latter pair seem destined to emerge in the middle to late 1980's as the optimum data transmission and processing system. Single mode fiber development and processing control must be improved. Connectors must be developed. Thin-film-fiber coupling problems must be solved. The payoff here is a wide band, high speed transmission system with greater flexibility and lower cost than presently offered by the graded index multimode systems. The ability to interface with integrated optics components also brings the many advantages of that technology into the single mode system.

Digital and analog optical communication systems for short haul transmission of voice, data and video signals appear to be the most promising near term application. Security of links will also attract near term deployment of systems addressing this problem.

The cost problem of fiber optic components seems destined to solve itself by increased volume production. In 1965, fiber technology represented a 1 million dollar market. Projections for 1980 are 86 million and for 1990 a 1.5 billion dollar market. Corning projects that graded-index fibers with under 5 db/km loss and greater than 500 MGz bandwidth could cost as little as 5 cents a meter in 500,000 km lengths in about 5 years. Costs to the military will very much depend on the decision of Bell Labs to begin conversion to fiber cables on a large scale basis.

The pace of development of Navy systems will depend very much on the transfer of this new technology to the design engineers. Thus far, most of the efforts within the Navy have been confined to a single laboratory, NELC. Other Navy laboratories have found it difficult to obtain funding in this area, or have simply remained ignorant of the tremendous potential that fiber optic technology offers. While the concept of lead laboratory is,in the author's view,a valid one, the full impact of fiber optics on numerous Navy platforms can only be rapidly achieved by making funding available to a wider number of investigators. This does not so much imply a reduction of the NELC budget as it does an overall increase in funding by the Navy in this area.

6.0 CONCLUSIONS

After a comprehensive review of the materials, optical fibers, cable designs, problem areas, advantages and payoffs of fibers and military systems employing or planned for fibers, it is possible to draw some firm conclusions:

1) Naval laboratories have played a key role during the past 5 years in initiating and formulating fiber optic technology for military systems, having foreseen early the significance of fiber optical communications.

2) Fiber optic technology is destined to impact broadly on many aircraft, shipboard, undersea and land based platforms within the next three to five years and beyond. Large scale deployment awaits reliable, qualified, ruggedized components, but these are forthcoming.

3) Rapid advances are being made in reducing both intrinsic fiber losses and stress optic losses, increasing fiber strengths and improving cable designs, so that none of these appear to loom on the horizon as critical problem areas.

4) Electromagnetic compatibility and increased bandwidth alone are sufficient to warrant the replacement of wires by fibers in many systems,but many other advantages clearly exist and have been documented in this report.

5) Standardization and mil-specs must be developed if large numbers of off-the-shelf optical components are to become available from various vendors during the next few years.

6) Civilian telecommunications efforts at Bell Laboratories and elsewhere throughout the world are destined to impact on many of the problems now being addressed and, more importantly,will significantly affect fiber component costs because of volume considerations.

7) A balanced program which addresses the broad range of Navy needs for all platforms is desirable. In particular, avionic and shipboard fiber data bus systems should be aggressively developed because of cost savings and increased performance.

8) The tow cable problem, while clearly representing the most difficult case faced by fiber technology within the Navy, still seems within reach during the next few years as strengths increase and cable losses decrease. All other Navy applications seem quite feasible.

9) Considering the payoffs of security, low cross talk, EMI and RFI immunity, increased range, increased bandwidth, EMP immunity, elimination of ground loops, ease of multiplexing, elimination of inductive and capacitive problems, reduction of number and size of submarine hull penetrations, etc., funding for fiber programs has not been excessive, and in many areas and laboratories totally inadequate. Broader support of fiber technology throughout the Navy will accelerate the spread and eventual deployment of fiber technology for Naval platforms.

7.0 FIBER OPTICS BIBLIOGRAPHY

7.1 General Reviews, Books and Conference Proceedings

1. M.K. Barnoski, Fundamentals of Optical Fiber Communications, Academic Press, New York (1976).

2. D. Gloge, Optical Fiber Technology, IEEE Press, New York (1976).

3. Proc. 1st European Conference on Fiber Optic Communications, IEE Publication No. 132 , London (1975).

4. Technical Digest, Topical Meeting on Optical Fiber Transmission, Williamsburg, Va., Optical Society of America, Washington (1975).

5. W.B. Allen, Fiber Optics: Theory and Practice, Plenum Press, London (1973).

6. D. Marcuse, Theory of Dielectric Optical Waveguides, Academic Press, New York (1974).

7. D. Gloge, Optical Fibers for Communication, Appl. Optics 13, 249 (1974).

8. S.E. Miller, E.A. Marcatili and T. Li, Research Toward Optical Fiber Transmission Systems Part I: The Transmission Medium; Part II: Devices and Systems Considerations, Proc. IEEE 61, 1703 (1973).

9. R.D. Maurer, Glass Fibers for Optical Communications, Proc. IEEE 61, 452 (1973).

10. C.P. Sandbank, The Challenge of Fiber Optical Communication Systems, Radio Electron. Eng. 43, 665 (1973).

11. N.S, Kapany and J.J. Burke, Optical Waveguides, Academic Press, New York (1972).

12. R. Kompfner, Optics at Bell Laboratories, Optical Communications, Appl. Optics 11, 2412 (1972).

13. D. Marcuse, Light Transmission Optics, Van Nostrand, New York (1972).

14. T. Li and E.A.J. Marcatili, Research on Optical Fiber Transmission, Bell Lab Rec. pp. 331-337 (December 1971).

15. D. Gloge, Optical Waveguide Transmission, Proc. IEEE 58, 1516 (1970).

16. K.C. Kao and G.A. Hochlam, Dielectric Fiber Surface Waveguides for Optical Frequencies, Proc. Inst. Elec. Eng. 113, 1151 (1966).

7.2 Optical Losses

1. P. Kaiser et al., Low Loss FEP Clad Silica Fibers, Appl. Optics 14, 156 (1975).

2. H.M. Presby, Materials Structure of Ge Doped Optical Fibers and Preforms, Bell Syst. Tech. J. 54, 1686 (1975).

3. W.G. French, et al., Optical Fibers with Very Low Losses, Bell Syst. Tech. J. 53, 9514 (1974).

4. G.W. Tasker and W.G. French, Low Loss Optical Waveguides With Pure Fused Silica Cores, Proc. IEEE 62, 1281 (1974).

5. D.N. Payne and W.A. Gambling, A New Silica Based Low Loss Optical Fiber, Electron. Lett. 10, 289 (1974).

6. K. Koizumi, et al., New Light Focussing Fibers Made by a Continuous Process, Appl. Optics 13, 255 (1974).

7. P.W. Black, et al., Measurements on the Properties of GeO_2-SiO_2 Cored Optical Fibers, Electron. Lett. 10, 239 (1974).

8. J.B. MacChesney, et al., A New Technique for the Preparation of Low Loss Step and Graded Index Optical Fibers, Proc. IEEE 62, 1280 (1974).

9. P. Kaiser, Drawing Induced Coloration in Vitreous Silica Fibers, J. Opt. Soc. Am. 64, 475 (1974).

10. W.B. French, et al., A Low Loss Fused Silica Optical Waveguide with Borosilicate Cladding, Appl. Phys. Lett. 23, 338 (1973).

11. D.A. Pinnow, et al., Fundamental Optical Attenuation Limits in the Liquid and Glassy State With Application to Fiber Optical Waveguide Materials, Appl. Phys. Lett. 22, 527 (1973).

12. P. Kaiser, et al., Spectral Losses of Unclad Vitreous Silica and Soda Lime Silicate Fibers, J. Opt. Soc. Amer. 63, 1141 (1973).

13. R.G. Smith, Optical Power Handling Capacity of Low Loss Optical Fibers as Determined by Stimulated Raman and Brillouin Scattering, Appl. Optics 11, 2489 (1972).

14. A.R. Tynes, et al., Low Mechanisms and Measurements in Clad Glass Fibers and Bulk Glass, J. Opt. Soc. Am. 61, 143 (1971).

7.3 Dispersion

1. J.A. Arnaud, Pulse Broadening in Multimode Optical Fibers, B.S.T.J. 54, 1179 (1975).

2. D. Gloge, Propagation Effects in Optical Fibers, IEEE Trans. Microwave Theory MTT 23, 106 (1975).

3. C. Pask et al., Number of Modes on Optical Waveguides, J. Opt. Soc. Amer. 65, 356 (1975).

4. R. Olshansky and D.B. Keck, Material Effects on Minimizing Pulse Broadening, Topical Meeting on Optical Fiber Transmission, Williamsburg, Va., (1975).

5. D. Gloge and E.A.J. Marcatili, Multimode Theory of Graded Core Fibers, Bell Syst. Tech. J. 52, 1563 (1973).

6. M. DiDomenico, Jr., Material Dispersion in Optical Fiber Waveguides, Appl. Optics 11, 652 (1972).

7. R. Olshansky, Mode Coupling Effects in Graded Index Optical Fibers, Appl. Optics 14, 935 (1975).

8. L.G. Cohen, Shuttle Pulse Measurements of Pulse Spreading in Optical Fibers, Topical Meeting on Fiber Optic Transmission, Williamsburg, Va.,Tu D1 (1975).

9. E.L. Chinnock, et al., The Length Dependence of Pulse Spreading in the Corning-Bell-10 Optical Fiber, Proc. IEEE 61, 1499 (1973).

10. W.A. Gambling, et al., Pulse Dispersion for Single Mode Operation of Multimode Cladded Optical Fibers, Electron. Lett. 10, 148 (1974).

11. D. Gloge, et al., Study of Pulse Dispersion in Selfoc Fibers, Electron. Lett. 8, 526 (1972).

7.4 Stress-Induced Optical Losses

1. D. Gloge, Optical Fiber Packaging and Its Influence on Fiber Straightness and Loss, Bell Systems Tech. J. (BSTJ) 54, 245 (1975).

2. D. Marcuse and H.M. Presby, Mode Coupling in an Optical Fiber with Core Distortions, BSTJ 54, 3 (1975).

3. R. Olshansky, Distortion Losses in Cabled Optical Fibers, Appl. Optics 14, 20 (1975).

4. J.A. Arnaud, Transverse Coupling in Fiber Optics, BSTJ 54, 1431 (1975).

5. W.B. Gardner and D. Gloge, Microbending Loss in Coated and Uncoated Optical Fibers, Topical Meeting on Optical Fiber Transmission, Williamsburg, Va., paper WA3 (1975).

6. C. Kao and G. Bickel, Effects of Tension in Multimode Optical Cable, ibid., paper WA7 (1975).

7. S. Geckeler and D. Schicketanz, The Influence of Mechanical Stress on the Transfer Characteristics of Optical Fibers, Optical Fiber Communication IEE Publ. No. 132, 51 (1975).

7.5 Strength of Fibers and Glasses - Fatigue Effects

1. B.K. Tariyal and D. Kalish, Strength Distribution in Low Loss Optical Fibers, Bull. Am. Ceram. Soc. 55, 9 (1976).

2. B.K. Tariyal et al., Proof Testing of Low Loss Optical Fibers, Bull. Am. Ceram. Soc. 55, 9 (1976).

3. C.R. Kurkjian, et al., Strength of 0.04-50 m Lengths of Coated Fused Silica Fibers, Appl. Phys. Lett. 28, 588 (1976).

4. H. Osanaie, et al., Tensile Strength of Optical Waveguide Fibers, Bull. Am. Ceram. Soc. 55, 9 (1976).

5. H. Schonhorn, et al., Organic Coatings of Optical Fibers for High Strengths, Bull. Am. Ceram. Soc. 55, 9 (1976).

6. C.R. Kurkjian, et al., High Strength Silica Fibers for Optical Communications, Bull. Am. Ceram. Soc. 55, 9 (1976).

7. U. Oestreich, The Application of the Weibull Distribution to the Mechanical Reliability of Optical Fibers for Cables, Optical Fibre Communication, IEE Publ. No. 132, 73 (1975).

8. R.D. Maurer, Strength of Fiber Optic Waveguides, Appl. Phys. Lett. 27, 220 (1975).

9. R.D. Maurer, et al., Optimization of Optical Waveguides - Strength Studies, ONR Contract Report N00014-73-C-0293, (January 1974).

10. R.L. Lebduska, Fiber Optic Cable Test Evaluation, Optical Eng. 13, 48 (1974).

11. E.K. Pavelchek and R.H. Doremus, Static Fatigue in Glass - A Reappraisel, Tech. Rept. for ONR Contract N00014-67-A-0117-0014, NR 032-531 (February 1975).

12. R.H. Doremus, et al., The Rate of Dissolution of Amorphous Silica in Water, Inaccessibility of Crack Tips in Glass, ibid., (June 1973).

13. R.H. Doremus, Glass Static Fatigue, Final Report ONR Contract N00014-68-C-0126 (August 1971).

14. J.E. Ritter and C.L. Sherburne, Dynamic and Static Fatigue of Silicate Glasses, ONR Contract N00014-68-A-0146-3 (December 1970).

15. Fundamentals of Massive Glass as a Naval Structural Material, NMAB Report No. 261 (March 1970).

16. B. Sugarman, Strength of Glass (A Review), J. Materials Science 2, 275 (1967).

17. R.E. Mould, The Strength of Inorganic Glass, In "Fundamental Phenomena in the Materials Sciences", Vol. 14, ed by L.J. Bonis, pp. 119-149 (1967).

18. V.R. Deitz, Interaction of Water Vapor With Pristine E-Glass Fiber, NRL Report 6812 (December 1968).

7.6 Cables

1. M.I. Schwartz, Optical Cable Design Associated With Splicing Requirements, Proc. 2nd European Conference on Optical Fiber Communication (September 1976).

2. S. Tanaka, et al., Properties of Cabled Low Loss Silicone Clad Optical Fibers, ibid., (September 1976).

3. P. Zimmerman, Insulated Fibre Optical Cables ibid., (September 1976).

4. G. LeNoane, Optical Fiber Cables and Splicing Techniques, ibid., (September 1976).

5. W.B. Gardner, et al., Design and Characterization of an Exploratory Fiber Optic Cable (September 1976).

6. R.A. Miller, Fiber Cabling, Topical Meeting on Fiber Optic Transmission, Williamsburg, Va., paper WA1 (1975).

7. M.I. Schwartz, Optical Fiber Cabling and Splicing, ibid., paper WA2 (1975).

8. R. Jocteur, Cabling of Low Loss Optical Fibers Optical Fibre Communication, IEE Publ. No. 132 79 (1975).

9. S. Maslowski, Development of Cables and Connectors for Optical Fibers, ibid., 64 (1975).

10. T. Nakahara, et al., Design and Performance of Fiber Optic Cables, ibid., 81 (1975).

11. M.I. Schwartz, Optical Fiber Parameters and Optical Cable Design Considerations, ibid., 201 (1975).

12. T. Mizukami, Spectral Loss Performances of Optical Fiber Cables Using Plastic Spacer and Metal Tube, ibid., 191 (1975).

7.7. Repeaters

1. W.E. Heinlein, et al., Repeater Spacings of Digital Communication Systems Using Optical Waveguides, Proc. IEE 123, 653 (1976).

2. S.D. Personick, Design of Repeaters for Fiber Optic Systems, In "Fundamentals of Optical Fiber Communication, pp. 183-204, Academic Press (1976).

3. C.Y. Boisrobert, et al., Digital Repeater Design, Optical Fibre Communication, IEE Publ. No. 132, 204 (1975).

4. W.E. Heinlein and H.R. Trimmel, Repeater Spacings of 8 M bit/s and 34 M bits/s Transmission Systems Using Multimode Optical Waveguides and LED's, Optical Fiber Communication, IEE Pub. No. 132, 177 (1975).

5. Y. Ueno, et al., A 40 Mb/s and a 400 Mb/s Repeater for Fiber Optic Communication, ibid., 147 (1975).

6. J. Yamagata, et al., A 32 Mb/s Regenerative Repeater For Fiber Cable Transmission, ibid., 144 (1975).

7. J.E. Goell, An Optical Repeater with High Impedance Input Amplifier, Bell Syst. Tech. J. 53, 629 (1974).

8. J.E. Goell, A 274-Mb/s Optical Repeater Employing a GaAs Laser, Proc. IEEE 61, 1504 (1973).

9. P.K, Runge, An Experimental 50 Mb/s Fiber Optic Repeater, Proc. ICC, Minneapolis, Minn. (1974).

10. S.D. Personick, Receiver Design for Digital Fiber Optic Communication Systems, Bell Syst. Tech. J. 50, 843 (1973).

11. F.M. Bands, et al., An Experimental 45 Mb/s Digital Transmission System Using Optical Fibers, Proc. ICC, Minneapolis, Minn. (1974).

12. T. Uchida, et al., An Experimental 123 Mb/s Fiber Optic Communication System, Proc. Topical Meeting in Fiber Optic Transmission, Williamsburg, Va., Paper Th A4 (1975).

7.8 Radiation Effects in Fibers

1. B.D. Evans and G.H. Sigel, Jr., Radiation Resistant Fiber Optic Materials and Waveguides, IEEE Trans. Nuclear Science, NS-22, 2462 (1975).

2. G.H. Sigel, Jr. and B.D. Evans, Prospects for Radiation Resistant Fiber Optics, Optical Fiber Communication, IEE Publ. No. 132, 48 (1975).

3. G.H. Sigel, Jr., A Review of Radiation Damage in Fiber Optics, Proc. All Naval Laboratories Fiber Optic Conference, NELC (22-23 October 1974).

4. E.J. Friebele, Radiation Protection of Fiber Optic Materials: Effect of Cerium Doping on the Radiation Induced Absorption, Appl. Phys. Lett. 27,210 (1975).

5. B.D. Evans, G.H. Sigel, Jr. and V.H. Ritz, Fiber Optic Glass Dosimetry, Trans. Amer. Nuclear Soc. 19, 46 (1974).

6. P.L. Mattern, et al., Effects of Radiation on Optical Fibers and Materials, IEEE Trans. Nuclear Science NS-22, 2468 (1975).

7. G.H. Sigel, Jr., et al., Radiation Effects in Fiber Optics Waveguides, NRL Memo Report 2934 (November 1974).

8. G.H. Sigel, Jr. and B.D. Evans, Radiation Induced Optical Degradation in Glass Fiber Waveguides, Proc. 10th Int. Congr. Glass 6, 23 (1974).

9. B.D. Evans and G.H. Sigel, Jr., Permanent and Transient Radiation-Induced Losses in Optical Fibers, IEEE Trans. Nuclear Science NS-21, 113 (1974).

10. P.L. Mattern, et al., The Effects of Radiation on the Absorption and Luminescence of Fiber Optic Waveguides and Materials, IEEE Trans. Nuclear Science NS-21, 81 (1974).

11. G.H. Sigel, Jr. and B.D. Evans, Effects of Ionizing Radiation on Transmission of Optical Fibers, Appl. Phys. Lett. 24, 410 (1974).

12. R.D. Maurer, et al., Radiation Effects in Fiber Optics. Appl. Optics 12, 2024 (1973).

13. G.H. Sigel, Jr., Radiation Effects in Optical Waveguides, NRL Memo Report 2704 (1973).

7.9 Military Applications of Fiber Optics

1. Preliminary Tri-Service Technical Application Area (TAA) Document on Fiber Optics Communication Technology, NELC (July 1, 1976).

2. F.C. Allard, A Fiber Optics Sonarlink, Electro-Opt. Systems Design, pp. 32-35 (February 1976).

3. P.J. Klass, Image Return Methods Tested for RPV's, Aviation Week (March 8, 1976).

4. W. Culver, Research on Optimum Optical Fiber for Torpedo Guidance, Proposal submitted to NELC (April 12, 1976).

5. J.R. Ellis, A-7 ALOFT Demonstration, Interim Report from March 1974 through December 1975, NELC TR 1968 (January 1976).

6. D.J. Albares, Potential Military Optical Fiber Communications, Optical Fibre Communication, IEE Publ. No. 132, 167 (1975).

7. D.J. Albares, L.V. Dworkin and K.C. Trumble, Prospective Applications for Fiber Optic Transmission in the Military, Topical Meeting on Fiber Optic Transmission, Williamsburg, Va., paper Th A1 (1975).

8. O.L. Doellner, Implementation of Fiber Optic Data Transmission Links in Aerospace Vehicles, Proc. National Aerospace and Electronics Conf., Dayton, Ohio (June 1975).

9. J. Hoss, et al., A Foreign Technology Assessment and Forecast: Fiber Optic Communications, 1978-1980, Report for CIA Contract XG-4040 (June 1975).

10. Tri-Service, Technical Application Area (TAA) Document on Fiber Optics Communications Technology, Draft, Rev. 1 (February 1975).

11. R.J. Kochanski and G.M. Holma, A-6E Fiber Optic Study, NELC TD 422, (April 1975).

12. J.H. Wildermuth, Fiber Optic Audio-Link Systems Aboard USS Plunger (SSN-595): Feasibility of Applying a Fiber Optics Transmission Line on a Submarine, NELC TD 425 (April 1975).

13. J.R. Ellis and R.A. Greenwell, A-7 ALOFT Economic Analysis Development Concept, NELC TD 435 (July 1975).

14. R.D. Harder, A-7 ALOFT Master Test Plan, NELC TD 438, July 1975.

15. D.B. Cambell, Use of Fiber Optics in Electro-Magnetic Pulse Systems, Proc. Electro-optical Systems Design Conference, Anaheim, Calif., pp. 686-691 (November 1975).

16. M.K. Zaman, et al., Developmental CP-901 Airborne Digital Computer Fiber Optic Interface for Potential Application in P-3C Aircraft,ibid., pp. 699-706 (November 1975).

17. F.C. Allard, A Wide Dynamic Range, Audio Frequency Fiber Optic Transmission Line (For Passive Sonar Submarine Systems), ibid., pp. 672-678 (November 1975).

18. D.E. Altman, Eight Terminal Bidirectional, Fiber Optic Trunk Data Bus, NELC TR 1969 (November 1975).

19. I.B. Slayton, et al., Fiber Optics Communication Link Study, Rome Air Development Center, Report RADC-TR-75-273 (November 1975).

20. F.R. McDivitt and I.B. Slayton, Optical Cable Communications Study, Rome Air Development Center, Report RADC-TR-75-187 (July 1975).

21. W.D. Scott, et al., Fabrication of Special Waveguide Shapes and Mechanical Properties of Glass Fiber Waveguides, Univ. Wash., ONR Report N00123-73-C-1200 (February 1975).

22. J.R. Biard, Optoelectronic Aspects of Avionic Systems II, Final Report, AFAL-TR-75-45 (May 1975).

23. Defense Documentation Center and Report on Fiber Optics Technology, Report No. ATL45C (October 1975).

24. C.M. Stickley, et al., Anticipated Uses of Fiber and Integrated Optics in the Defense Department, Digest of Technical Papers, Topical Meeting on Integrated Optics, New Orleans, paper WB1 (1974).

25. R.E. Munn and T.A. Meador, Fiber Optics Remote Link for AN/PPS-18 Radar, NELC TD 314 (August 1974).

26. Fiber Optic Interconnections for Electronic Systems of 2000-Ton Surface Effects Ship 2KSES NELC TD 333 (June 1974).

27. J.D. Anderson, Fault Tolerant Digital Airborne Data System Flight Test, Hughes Aircraft Tech. Report AFFOL-TR-74-122 (December 1974).

28. W.M. Caton, Integrated Optical Circuit Components, NELC TR 1931 (September 1974).

29. H.F. Taylor, W.M. Caton and A.L. Lewis, Fiber Optics Data Bus System, NELC TR 1930 (August 1974).

30. A-7 ALOFT Demonstration Plan (prepared by Control Data Corp.) NELC TD 369 (October 1974).

31. R.L. Lebduska and G.M. Holma, Fiber Optic Cable Hardware Test, NELC TR 1900 (December 1973).

32. W.E. Martin and D.J. Albares, Fiber and Integrated Optic Communication Technology, NELC TR 1891 (August 1973).

33. R. Lebduska and G. Holma, Fiber Optic Cable Connector Test Evaluation, NELC TN 2367 (May 1973).

34. R.L. Lebduska, Fiber Optic Cable Test, NELC TR 1869 (March 1973).

35. R.A. Andrews, A.F. Milton and T.G. Giallorenzi, Military Applications of Fiber Optics and Integrated Optics, IEEE Trans. Microwave Theory and Techniques, MTT 21, 763 (1973).

36. R.D. Maurer, B.D. Keck and B.J. Todd, Optimization of Optical Waveguides, Electro-Optic Studies, Corning Glass Works, ONR Contract N00014-73-C-0293 (Dec. 1973).

37. H.F. Taylor, Transfer of Information on Naval Vessels Via Fiber Optics Transmission Lines, NELC TR 1763 (May 1971).

38. R.A. Andrews, Optical Waveguides and Integrated Optics Technology, NRL Report 7291 (August 1971).

39. R.S. Katz, An Investigation of the Potential Application of Sapphire Filaments for the Mechanical Strengthening of Fiber Optic Bundle and Cable Systems, NAFI TR-2063 (May 1975).

40. R.S. Katz, The Use of Sapphire Filaments for Strengthening Fiber Optic Cables, Preliminary NAFI Report (April, 1976)

APPENDIX I

TRI-SERVICE FIBER OPTIC ORGANIZATION

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1860 Wiehle Avenue
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437-2461

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AUTOVON: 993-5404/5288

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ATTN: Code 220
San Diego, CA 92152
AUTOVON: 933-2786

Mr. K.C. Trumble
Air Force Avionics Laboratory
ATTN: AFAL/AAT
Wright-Patterson AFB, Ohio 45433
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C. WORKING GROUPS

1. CABLES, CONNECTORS, SPECIAL DEVICES

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AUTOVON: 785-4098

2. SOURCES AND DETECTORS

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3. RADIATION EFFECTS

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Washington, D.C. 20375
AUTOVON: 297-2870

LT K.J. Soda
Air Force Weapons Laboratory
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Kirtland AFB, New Mexico 87117
AUTOVON: 964-0316

4. STANDARDS, SPECIFICATIONS, RELIABILITY, TESTING

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Mr. T. Dellecave (Reliability)
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5. COMMUNICATIONS SECURITY

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Mr. Patrick Benson
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Fort George G. Meade, MD 20755
AUTOVON: 235-6931

Mr. James A. Rupp
National Security Agency, S13
Fort George G. Meade, MD 20755
AUTOVON: 235-6079

APPENDIX II

KEY LABORATORIES AND KEY PERSONNEL IN OPTICAL FIBER TECHNOLOGY

This summary has included Navy and related industrial efforts. The Army program is centered at ECOM, Fort Monmouth, N.J. and the Air Force Program at the Avionics Laboratory, Wright Patterson AFB, Dayton, Ohio. Only research and development work on the fiber optic cables is included.

A. Navy Laboratories

1) NELC, San Diego, CA 92152

NELC functions as the lead Navy Lab in 6.2 Fiber Optic Technology with about 80-85% of the funding in this area. Principal sources of support have been NAVAIR, NAVELECS, ARPA and NSA, with lesser amounts coming from numerous other sources. NELC is responsible for the broad advance of Fiber Technology from the laboratory to the fleet. Accomplishments have included development of FO components, cost analysis, avionic and shipboard demonstrations, establishment of fiber testing procedures and milstandards, coordination of the Tri-Service FO Committee and efforts at FO technology transfer by cooperative efforts in areas such as undersea cables, sonobuoys, torpedo guidance and secure communications. Some of the key people in the NELC program are listed below.

Name	Code	Phone (Autovon)	Responsibility
Don Williams	220	933-2786	Head, Fiber Optic Technology Program
Don Albares	2500	933-6641	Optical Fibers Strength of Fibers
Henry Taylor	2500	933-6641	Integrated Optics
Howard Rast	2500	933-6641	Optical and Mechanical Testing
Bob Lebduska	4400	933-2640	Environmental Testing Tri-Service Standards
Dick Eastley	2500	933-6400	Under Sea Cables Strength of Fibers
Bob Harder	1640	933-7553	A-7 Program
LT Bill Gadino	1500	933-6719	Intelligence and Security Programs
Terry Meador	2540	933-7740	Manufacturing and Technology Program
George Kosmos	4400	933-2640	Fiber Optic Cables

2) NRL, Washington, D.C. 20375

NRL currently has a variety of 6.1 and 6.2 programs related to the development and characterization of fiber optic materials and waveguides. On-going programs in the Materials Sciences Division include development of moderate loss, high index,radiation resistant silicate glasses for optical fibers, radiation testing of fiber optic cables and the drawing of low loss silica and silicate glass fibers. In the Optical Sciences area programs on single multimode fiber systems, single mode technology, access couplers, integrated optics and fiber-to-film coupling are being pursued. Smaller efforts include those on the strength of glass in the Engineering Materials Division and on light scattering and acousto-optic interactions in the Acoustics Division. Key personnel engaged in these programs are listed below.

Name	Code	Phone (Autovon)	Responsibility
Bob Ginther	6445	297-3487	Preparation of Fiber Optic Grade Glasses

E.J. Friebele	6444	297-2270	Optical Fiber Drawing and Optical Measurements, Fiber Coatings
George H. Sigel, Jr.	6444	297-2870	Radiation Effects in Fibers, Optical Properties
Tom Giallorenzi	5570	297-3209	Single Fiber and Single Mode Technology, Integrated Optics
Fenner Milton	5504	297-3011	Fiber Optic Technology, Coupling Problems
Roy Rice	6360	297-2131	Strength of Glass
Joe Bucaro	8131	297-7336	Light Scattering in Fiber Optic Materials
Jim Griffith	6120	297-2529	Polymers
Bob Stone	5424	297-3454	PTTI Fiber Links

3) NUC, Kailua, Hawaii 96734
San Diego, CA 92132

NUC has been engaged in a joint effort with NELC to develop fiber optic cables for undersea applications. Applications include towed arrays, bottom laid cable, tethers for search and mapping systems and sophisticated weapon or inspection systems. First generation deep sea cables have been designed and procured and are in the process of being tested at NELC. Strength, strain and stress-induced cabling losses are being studied. Contacts at NUC are

George Wilkins
Naval Undersea Center
Hawaii Laboratory
P.O. Box 997
Kailua, Hawaii 96734

Steve Cowen
Naval Undersea Center
Code 6513
San Diego, CA 92132

4) NAFI, Indianapolis, Indiana 46218

The first Navy funding specifically for fiber optics was given to NAFI in 1970 by NAVAIR to study the possible use of fiber optics in aircraft multiplex data links as

part of the NAVAIR Solid State Electric Logic (SOSTEL) system effort. NAFI has been responsible for the design and development of fiber optic connectors and hardware for avionic applications. NAFI has worked with NELC to establish mil specs for fiber optics used in avionic applications and on the development of the Navy fiber optics manufacturing program which is directed at the development of cables for internal aircraft data transmission. The principal investigator at NAFI is

Mr. Rod Katz
Applied Research Department
Department 813
(313)353-3787

5) NUSC, Newport, Rhode Island 02840

A program was established at NUSC in FY 1975 to install multimode fiber optics in a submarine sonar system. Off-the-shelf components were utilized and have not been optimized or military qualified. In spite of these limitations, work to date on a 52 channel link installed on a test submarine for a sonar array has indicated the superiority of the fiber system. Principal advantages are smaller size, reduced weight, greater bandwidth and EMI immunity. The reduced size and number of hull penetrations is also noteworthy. A new joint NUSC-NELC program is aimed at the development of fiber torpedo guidance cable for the Mark 48 torpedo. The principal investigator at NUSC is

Fred Allard SA 33
(203)442-0711, Ext. 2192

6) Naval Air Development Center (NADC)
Johnsville, Warminster, PA 18974

NADC presently sponsors a number of fiber optic programs via NAVAIR which deal with avionic and ASW problems. These include a program with NAFI for the development of optical cable systems for Naval aircraft, in particular SOSTEL II data handling systems. There is a joint effort with NELC and NUC to develop a sonobuoy cable for long range undersea target surveillance. NADC is studying the use of fiber cables on the P-3C patrol aircraft scheduled for FY 1979 production. A small program also exists to evaluate the use of optical fibers for remote inspection of aircraft surfaces. Contacts at NADC include:

	AUTOVON	
Gary Averill	441-2289	P-3
E. Rickner	441-7419	Avionic Systems SOSTEL II
R. Hollar	441-2135	Sonobuoy cable
T.R. Trilling	441-2580	P-3, VFAX

7) Naval Coastal Systems Laboratory (NCSL)
Panama City, FL

NCSL is engaged primarily in work involving mine warfare, coastal technology, tow cables and swimmer technology. There is presently an effort to develop a fiber optic cable for sonar applications with a 200 MHz bandwidth. Another area of interest relates to utrasonic image conversion for diver facemasks. The contact at NCSL is

Herb Larrimore
AV436-4481

8) Other Navy Labs

Smaller efforts related to fiber optic technology exist at NWC, China Lake who assisted on the A-7 demonstration, NSWC Dalgren for an Electromagnetic Vulnerability Assessment Project and NSRDC, Annapolis for fire resistant and non-toxic materials work and new programs have no doubt been initiated which are unknown to the author.

9) Navy Program Managers and Funding Officers

Name	Agency	Code	Phone
Andrew Glista	NAVAIR	52022G/360G	222-2511
G. Tsaparas	NAVAIR	340D	222-7419
James Willis	NAVAIR	778	222-7414
R. Retta	NAVAIR	5202	222-7640
F. Lueking	NAVAIR	360A	222-2511
Larry W. Sumney	NAVELEX	03042	222-8741
B. Martin	NAVELEX	03103	222-3567
N. Horowitz	NAVELEX	51014	222-8486
M. Wapner	NAVSEA	0341	222-1174
H. Dimattia	NAVSEA	03526	222-4417
CDR W. Hodkins	ONR	411	222-4417
J.O. Dimmock	ONR	427	222-4216
A.M. Diness	ONR	471	222-4401
CAPT H. Winsor	DARPA	MSO	224-3031

10) Other Services

Army Contact

Dr. Rudolf G. Buser
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Dayton, Ohio 45433
AV 785-4594

APPENDIX II (continued)

B. Industrial Research Laboratories

1) Bell Laboratories

Bell Labs has the largest and most advanced effort in the world in the area of optical communications. Their programs range from fundamental materials efforts and light propagation studies to the development of complex cables and systems. The Bell Fiber effort is centered primarily at three laboratories: 1) Murray Hill,which is concerned with materials development and the drawing and characterization of optical fibers, 2) Crawford Hill, Holmdel,which is concerned with fiber optic telecommunications and technology, and 3) Norcross, Georgia (Atlanta),which is responsible for cable and advanced systems development. While not engaged in any military problems directly, it has been our experience at NRL that the Bell scientists have been the most knowledgeable and most helpful of any of the many contacts which we have made in the fiber optic field. The major effort at Bell is focused on the development of low loss, large bandwidth (graded index and single mode) fibers for long distance telephone communications. A few of the key personnel at the three laboratories are listed below.

a) Murray Hill Lab (201-582-6121/2378)

Bill French	Fiber Materials, CVD
John Williams	Fiber drawing and processing
John Carruthers	Mgr. Fiber Optics Program
Chuck Kurkjian	Glass Technology, Strength of Fibers

b) Crawford Hill Lab., Holmdel, NJ

Steward Miller	Fiber Systems
Enrico Marcatili	Fiber Technology
Tinge Li	Fiber Transmission
Detlef Gloge	Fiber Propagation

c) Norcross, Georgia Lab

D. Kalish	Fiber Cabling
B.K. Tariyal	Fiber Strength

2) Corning Glass Works, Corning,NY 14830 (607-974-3150)

Corning was the first laboratory to develop low loss optical fibers by use of doped silicas (1970). They continue to have a strong effort in the optical fiber area but being primarily a glass company do not have as broad an effort as Bell Labs. Corning has provided a number of cables for both the Navy and Army programs. The basic

Corning fiber consists of a Ge doped silica core with a silica cladding and is available in either step index or graded index form. Principal efforts at present are directed towards achieveing consistent low losses, increased strengths, a minimum of microbending losses and good process control. Some key personnel are:

Peter Schultz	Fiber Optic Materials
Robert Maurer	Mgr. Fiber Optics, Strength of Fibers
Robert Olshansky	Fiber Propagation
Donald Keck	Measurements
Bart Bielawski	Fiber Technology
Frank Thiel	Fiber Systems, Couplers, Connectors

3) International Telephone and Telegraph, Electro-Optical Products Division, Roanoke, Va. 24019 (703-563-0371)

ITT also has a very broad capability in fiber technology just as does Bell Labs. The ITT effort in the U.S. received a substantial boost from the experience gained by the company in Britain at their Standard Telecommunications Laboratory (STL),where waveguide technology was actually first started. Dr. Charles Kao moved from STL to Roanoke only a few years ago. ITT is presently producing the strongest optical fibers yet available, has successfully bid on a number of Navy contracts and has made excellent progress in the past two years. Both fibers and cables are manufactured as well as other electro-optic components required for optical communication systems. Some of the staff are listed below.

Mokthar Maklad	Fiber Materials
K. Charles Kao	Fiber Waveguides
Gary Bickel	Fiber Measurements, Strength
Jim Goell	Fiber Systems and Technology

4) Dupont Corporation, Plastics Department, Wilmington, Delaware, 19898 (302-774-6339)

Dupont is the only laboratory with a research program on plastic optical fibers. They have marketed a PFX 0715 fiber with a PMMA core which has a minimum loss of 470 db/km (at 670 nm). Losses as low as 100 db/km seem attainable and are being worked on. Dupont also is producing plastic-clad silica fibers. Dupont plays a key role in the fiber industry because they supply most of the coating and jacketing materials currently being employed. A further reduction in optical losses of plastic fibers would substantially increase their importance for military applications,since breakage is uncommon. Dupont has recently expressed more interest in cooperative efforts with military laboratories. Personnel in the plastics department include:

Henry Beasely	Fiber Materials, Drawing
Fred Mannis	Plastic, Plastic Coated Fibers
Ron Ferguson	Coatings and Buffer Materials

There are numerous other companies with smaller efforts in the optical fiber area with new entries appearing each month. Some of these domestic manufacturers are listed below with a contact point when available.

5)	Galileo Electro-Optics. Corp. Sturbridge, MA 01518 (619-347-9191)	Optical Fibers Fiber Bundles Electro-Optic Components Fiber Faceplates
	Ishwar Aggarwal Rod Anderson	Fiber Optic Materials Fiber Products
6)	Valtec Corporation West Boyleston, MA 01583 (617-835-6082)	Silicate Glass Fibers and bundles Polymer Clad Silicas, Fiber Cables
	M. Acharekar	Fiber Optic Materials
7)	Hughes Research Labs. Malibu, CA 90265	(In-house Research)
	Doug Pinnow	Optical Fibers, High Strength, Metal Coating
	Michael Barnoski	Fiber Systems, Integrated Optics
8)	Fiber Communications, Inc. (FCI) Orange, NJ 07050 (201-678-8143)	Low loss fibers, fiber products
	Frank Dabby	
9)	Fiber Optic Cable Corp. (FOC) Framingham, MA 01701 (617-875-5530)	Low loss fibers
	Sheldon Glazer	
10)	American Optical Corporation Southbridge, MA 01550 (617-765-9711) Fiber Optics Division	Silicate Glass Fibers, Program for low to Moderate Loss High NA fibers.
11)	Schott Glass, Inc. Duryea, PA 18642 (717-457-7485)	Worlds largest manufacturer of fiber optical glasses, broad range of fibers from Germany

12)	Amersil, Inc. Hillside, NJ 07205 (201-688-4500)	Markets Hereaus-Schott Synthetic silicas, Suprasil Suprasil W, TO8 for low loss fibers

The following companies are engaged in various fiber programs related to military systems. This is clearly only a partial listing.

13)	IBM Corporation Federal Systems Division Oswego, NY 13827 R. Betts (607-755-1325)	A-7 Fiber Optic Hardware
14)	LTV Aerospace Corp. Vought Systems Division Dallas Texas 75222 T. Coleman (214-266-3770)	A-7 Fiber installation and ground tests
15)	TRW Redondo Beach, CA 90278 R.L. Johnson (213-536-2622)	Optical Detection of Sound in Water
16)	Air Logistics Corporation Pasadena, CA 91109 R. Considine (213-795-9971)	Undersea Fiber Optic Cables
17)	Intelcom Rad Tech San Diego, CA 92138 Carl Porter (714-565-7171)	SGEMP-EMP Hardening Techniques Using Optical Fibers
18)	OPTELCOM, Inc. Gaithersburg, MD 20760 Bill Culver (301-948-4232)	Missile, RPV and Torpedo Guidance Using Fiber Tethers
19)	Hughes Aircraft Culver City, CA John D. Anderson B. Diener	Avionic Fiber Systems Intrusion Resistant Fiber Optic Communications
20)	Lockheed Aircraft Burbank, CA M.K. Zaman	P-3C Aircraft Fiber Optic System
21)	Boeing Aerospace Corp. Seattle, WA O. Doellner	Fiber Optic Missile and Aircraft Systems
22)	Arthur D. Little, Corp. Cambridge, MA 02140 John Haggerty (617-864-5770)	Infrared Transmitting Fiber Optics

23)	Harris-Intertype Melbourne, FL Fred R. McDivitt	Intrusion Resistant Fiber Optic Communications
24)	Simplex Cable Co. Portsmouth, NH 03801 (603-436-6100) L. Hutchins	Undersea Cables

C. University Research With Navy Support

	Research Areas
Dr. Pedro Macedo Catholic University Vitreous State Lab Washington, DC 20017 (202-635-5327)	Fiber Materials Graded Index Fibers Light Scattering Strength of Glass
Dr. William Scott University of Washington Department of Ceramic Engineering Seattle, WA 98105	Fiber Waveguides Strength of Fibers
Dr. John E. Ritter, Jr. University of Massachusetts Amherst, MA 01002	Strength of Glass Static and Dynamic Fatigue
Dr. Robert H. Doremus Rensselaer Polytechnic Institute Department of Materials Science Troy, NY 11081	Strength of Glass Stress Corrosion
Dr. A. Yariv California Institute of Technology Pasadena, CA	Optical Waveguides Integrated Optics